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Indian Standard

GUIDE TO THE MEASUREMENT OF EQUIVALENT ELECTRICAL PARAMETERS OF QUARTZ CRYSTAL UNITS

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Piezoelectric Quartz and Ceramic Devices for Frequency Control and Selection Sectional Committee, LTD 12

NATIONAL FOREWORD

This Indian Standard which is identical with IEC 61080 (1991) 'Guide to the measurement of equivalent electrical parameters of quartz crystal units' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendations of the Piezoelectric Quartz and Ceramic Devices for Frequency Control and Selection Sectional Committee and approval of the Electronics and Telecommunications Division Council.

The text of the IEC Standard has been approved as suitable for publication as an Indian Standard without deviations. Certain conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.

b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

CROSS REFERENCE

In this adopted standard, reference appears to the following International Standard for which Indian Standard also exists. The corresponding Indian Standard which is to be substituted in its place is given below along with its degree of equivalence for the edition indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 302 (1969) Standard definitions and methods of measurement for piezoelectric vibrators operating over the frequency range up to 30 MHz	IS 7962 : 1975 Methods of measurement for piezoelectric vibrations operating over the frequency range up to 30 MHz	Technically equivalent

The Technical Committee responsible for the preparation of this standard has reviewed the provisions of the following International Standards and has decided that these are acceptable for use in conjunction with this standard:

IEC 283 (1968) Methods for the measurement of frequency and equivalent resistance of unwanted resonances of filter crystal units

IEC 444 Measurement of quartz crystal unit parameters by zero phase technique in a π-network

IEC 444-1 (1986) — Part 1 : Basic method for the measurement of resonance frequency and resonance resistance of quartz crystal units by zero phase technique in a π-network

IEC 444-3 (1986) — Part 3 : Basic method for the measurement of two-terminal parameters of quartz crystal units up to 200 MHz by phase technique in a π-network with compensation of the parallel capacitance C_0

IEC 444-4 (1988) — Part 4 : Method for the measurement of the load resonance frequency f_L, load resonance resistance R_L and the calculation of other derived values of quartz crystal units, up to 30 MHz

IS 15544 : 2004
IEC 61080 (1991)

Indian Standard

GUIDE TO THE MEASUREMENT OF EQUIVALENT ELECTRICAL PARAMETERS OF QUARTZ CRYSTAL UNITS

1 Scope

This Standard constitutes a guide to the measurement of equivalent electrical parameters of quartz crystal units.

2 Equivalent network

Consisting of a mechanically resonant piezoelectrically excited quartz element together with some means of mechanical mounting within a protective enclosure, a crystal unit can be exactly represented by an equivalent two-port network as shown in figure 1. In this network, C_{p1} and C_{p2} represent the electrical capacitance between each connecting pin and the surrounding ground planes (the enclosure itself, if made from a conducting material). C_{pp} represents the capacitance directly between the contacting pins. R_{p1} and R_{p2} are the equivalent resistances of the mounting structures which support the quartz element, while L_{p1} and L_{p2} are the equivalent inductances of these structures. C_e represents the electrical capacitance between the two electrodes, while C_{e1} and C_{e2} are the capacitances between each electrode and the surrounding ground planes. R_s represents conductivity between the electrodes of the resonator, due to a leakage path. In the case of quartz resonators at moderate frequencies, R_s can usually be neglected (except if there are defects in the plating masks), but it may be significant for high frequency, high overtone quartz crystal units.

The series resonant branches represent the equivalent electrical parameters associated with each mechanical resonance of the quartz plate. Since quartz plates are of finite dimensions, there will be a large number of resonant modes, many of which can be excited piezoelectrically, and others which can be excited by mechanical coupling to other modes. One of these resonances will correspond to the "design mode" of vibration; the others will be "spurious" or "unwanted" modes for that application, and will correspond to other overtone modes of thickness shear, width shear, extentional and flexure vibrations as well as the anharmonic modes of thickness shear and thickness twist.

While this model of a crystal unit is quite complete, and capable of describing its electrical response over a very wide frequency range, it is fortunate that this degree of sophistication is rarely, if ever, needed. In the remainder of this standard, we will consider three degrees of simplification from this very general equivalent circuit, and discuss some of the applications for which each is suitable.

3 Simplified equivalent networks

In most cases, the response of the crystal unit to applied electrical signals needs be considered over only limited frequency ranges, which will include the "design mode" frequency and may include one or more of the other "unwanted" modes. The frequency range of interest may extend above and below the desired mode frequency by only a fraction of a percent, or in the case of a filter application, a range of several percent may be required. If the application is a filter circuit, or a voltage-controlled or temperature-compensated oscillator circuit, more exact modelling of the crystal response over the frequency band of interest may be needed. For these applications, the equivalent network of figure 2a is usually suitable. Here, the shunt capacitances between pin and ground and between electrode and ground are not distinguished.

The residual inductance and resistance of the mounting structure are not separately detailed, but are included in the equivalent motional parameters of the crystal unit. Since the frequency band of interest is relatively narrow, this will introduce little error. However, it is well for the circuit designer to be aware of the more complex network topology, as occasional spurious circuit behaviour can sometimes be explained by consideration of the entire equivalent circuit of figure 1. (For example, very high frequency oscillation can occur due to L_{p1} and L_{p2} together with the shunt capacitances to ground resulting in some kind of failure of the design mode resonance!) While filter applications in particular may require specification of one or more of the "unwanted" modes, it is usually sufficient to ascertain that their resonance frequency lies outside a particular narrow band and/or their equivalent series resistance is greater than some specified value. It will in general be necessary to evaluate the capacitance between pins and ground (C_{13} and C_{23}) as well as the total capacitance between pins (C_0). Motional resistance (R_1) and motional inductance (L_1) are of prime importance as they determine the band-shape characteristics of the filter, or the frequency tuning characteristics and gain margins of the circuit.

At high frequencies (above about 100 MHz) the effect of the inductance of mounting leads in combination with the capacitances from pins to case and electrode structure to case transforms the actual motional parameters of the quartz element, so that the equivalent parameters measured at the reference plane (2 mm below the seating plane of the enclosure) are somewhat different. The addition of a shunt conductance between pins in the equivalent circuit is usually sufficient to model the effect, as the applications circuit will only be aware of the effective parameters at the reference plane, and the fact that the motional equivalent parameters seen at this point differ somewhat from those of the quartz element alone is not significant.

For those cases which require good modelling of the crystal unit in a filter circuit or in a tunable oscillator application, then the parameters which are needed are:

- series resonance frequency, f_s;
- motional resistance, R_1;
- motional equivalent inductance, L_1 (or capacitance C_1);
- shunt conductance, G_0;
- shunt capacitance, C_0;
- pin-to-case capacitances, C_{13} and C_{23}.

In some instances, it will also be required to determine the frequencies and the effective resistance of one or more unwanted modes which are located near the design mode frequency.

For somewhat less exacting applications, such as in simple narrow-band filters where only the pass-band shape is critical, or in oscillators which will operate at fixed frequency, the equivalent circuit can be further simplified. As shown in figure 2b a two-terminal equivalent which neglects the pin-to-case capacitances may suffice. In this case, however, it is well to specify whether or not the enclosure will be connected to the same point as one of the crystal leads, as the value of C_0 will depend upon how the connections are made. If the unit is measured with the enclosure ungrounded, the C_0 value will include the two pin-to-case capacitances in series; if both the enclosure and one crystal unit lead are to be connected to the same point in use, the effective C_0 value will be different.

The parameters needed for the equivalent circuit of figure 2b which will allow reasonable modelling of the crystal response over a frequency range of a few percent near f_s are:

- series resonance frequency, f_s;
- motional resistance, R_1;
- motional inductance, L_1 (or capacitance, C_1);
- effective shunt capacitance, C_0.

However, in many oscillator applications, it is sufficient to determine the resonance frequency (at which the transfer phase is zero) together with the insertion resistance at this frequency; or, if the oscillator uses a fixed value of load capacitance, the load resonance frequency and load resonance resistance at the specified load capacitance are all that are required. The equivalent circuit for these cases may be represented as in figure 2c. The effective motional parameters for the case of resonance operation are essentially the same as those of the series branch in figure 2b; however, for the case of operation with a load capacitor, resistance and inductance as well as frequency are different. As will be discussed later, measurement of the load parameters poses some special problems.

When figure 2c represents the series resonance condition, it will be found adequate to predict behaviour at frequencies very near resonance, where the impedance of the series resonance branch is small compared to the impedance of the shunt capacitance C_0, and the figure of merit of the crystal unit is greater than about 10:

$$M = \frac{1}{\omega_s C_0 R_1} >> 10$$

where

ω_s is the angular series resonance frequency $= 2\pi f_s$

C_0 is the shunt capacitance

R_1 is the motional resistance.

This condition will usually be met by most quartz crystal resonators operating on fundamental, third or fifth mechanical overtones at frequencies below about 150 MHz.

4 Impedance/admittance characteristics

A very complete discussion of the impedance function and characteristic frequencies of the crystal unit equivalent network can be found, for example, in references [1]* and [2]*. Consequently, we will not repeat the detailed derivations here; rather, we will look only briefly at those characteristics which are important when evaluating measurement techniques.

Examination of the network of figure 2a shows first, that the problems of measurement will be manifest mainly in the determination of the transadmittance, as the shunt capacitances (C_0, C_{13}, C_{23}) can be readily determined with a guarded capacitance bridge at a frequency well removed from any resonance phenomena. The motional arm, however, cannot be measured independently - it is always associated physically with the static elements.

The admittance of the motional arm can be written as:

$$Y'_{12} = \frac{1}{Z'_{12}} = \frac{1}{R_1 + j\left(\omega L_1 - \dfrac{1}{\omega C_1}\right)} \qquad (1)$$

while the admittance of the shunt capacitance C_0 and conductance G_0 are:

$$Y''_{12} = G_0 + j\,\omega\, C_0$$

where G_0 represents any shunt conductance which might be present across the resonator terminals due to traces of metallization or due to the effects of the mounting structure, and

$$\omega = 2\pi f.$$

Combining these, the total transadmittance is

$$Y_{12} = G_0 + \left(\frac{R_1}{R_1^2 + U^2}\right) + j\left(\omega\, C_0 - \frac{U}{R_1^2 + U^2}\right) \qquad (2)$$

where $U = \omega\, L_1 - \dfrac{1}{\omega\, C_1}$. Making use of the narrow band approximation, this can be simplified:

$$\omega\, L_1 - \frac{1}{\omega\, C_1} \approx 2\,\Delta\,\omega\, L_1$$

where $\Delta\omega = \omega - \omega_s$, the angular frequency offset from series resonance frequency.

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* The figures in square brackets refer to clause 16: Bibliography.

Substitution in equation (2) gives:

$$Y_{12} = G_0 + \frac{R_1}{R_1^2 + (2\,\Delta\,\omega\,L_1)^2} + j\left[\omega_s\,C_0 - \frac{2\,\Delta\,\omega\,L_1}{R_1^2 + (2\,\Delta\,\omega\,L_1)^2}\right] \tag{3}$$

which is the parametric equation of a circle in the Y-plane, of radius $1/2R_1$, centred at $G = G_0 + 1/2R_1$, $B = \omega_s C_0$, as shown in figure 3. The five characteristic frequencies often discussed are also shown in figure 3, and their location on the admittance circle is also indicated. The offset of the circle from the real axis has been exaggerated to demonstrate the differences.

The five characteristic frequencies are:

- f_m : frequency of minimum impedance;
- f_s : series resonance frequency;
- f_r : frequency of zero insertion phase at resonance (resonance frequency);
- f_a : frequency of zero reactance at anti-resonance (anti-resonance frequency);
- f_n : frequency of maximum impedance.

Clearly, one may determine the magnitude of Y_{12} at these characteristic frequencies directly from the transadmittance circle in the Y-plane. However, the motional inductance L_1 (capacitance C_1) requires knowledge of the frequency as well. Over the frequency range from f_r to f_a, the susceptance is negative; this portion of the curve transforms to a positive reactance in the Z-plane and is the only frequency range over which the crystal unit can exhibit a positive (inductive) reactance.

It should also be noted that of the five frequencies defined, only f_s is invariant with changes in stray static capacitance. The others all depend on the value of C_0, and will generally be different when the crystal unit is connected to a different fixture or circuit.

The relationships among these frequencies, in terms of the series resonance frequency, are given below:

$$\frac{f_s - f_m}{f_s} = \frac{\sqrt{1 + 4a^2} - 1}{4r} \approx \frac{a^2}{2r} \tag{4}$$

$$\frac{f_r - f_s}{f_s} = \frac{1 - \sqrt{1 - 4a^2}}{4r} \approx \frac{a^2}{2r} \tag{5}$$

$$\frac{f_a - f_s}{f_s} = \frac{1 + \sqrt{1 - 4a^2}}{4r} \approx \frac{(1 - a^2)}{2r} \tag{6}$$

$$\frac{f_n - f_s}{f_s} = \frac{1 + \sqrt{1 + 4a^2}}{4r} \approx \frac{(1 + a^2)}{2r} \qquad (7)$$

where

$$a = \frac{C_0 R_1}{\omega_s L_1 C_1} = \frac{r}{Q} \quad \text{and} \quad r = \frac{C_0}{C_1}$$

We see that the frequency of minimum impedance is slightly less than f_s, and the resonance frequency of zero phase is greater than f_s, the differences being a function of the quality factor Q and the ratio of capacitances (C_0/C_1). To illustrate the magnitudes, assume first a fundamental crystal unit of good quality, with $r = 200$, $Q = 400\,000$. The separation between f_m and f_s, and between f_r and f_s will be less than 1×10^{-9}. However, for an overtone crystal with $r = 5\,000$ and $Q = 30\,000$ the separation will be about $2{,}8 \times 10^{-6}$. Whether or not these frequency definitions may be used interchangeably will clearly depend upon the tolerances required, and the parameters of the crystal unit. (The high impedance frequencies f_a and f_n are rarely specified, as they depend strongly on the shunt capacitance, and therefore will usually be much different when connected into a user circuit than when placed in a test fixture.)

Figure 4 is a symbolic plot of the magnitudes of the real and imaginary components of crystal transimpedance, Z_{12}, again indicating the characteristic frequency points defined above.

Information about the value of the motional inductance/capacitance is contained in the relationships of figure 4. While the locus of the admittance-plane circle depends only on the magnitude of R_1 and the ratio of C_0 to C_1, the separation between the characteristic frequencies and the slope and magnitude of the reactance/impedance functions depend on the value of L_1 as well. We have already seen (equations (4), (5) and (6)) that:

$$\frac{f_s - f_m}{f_s} = \frac{f_r - f_s}{f_s} \approx \frac{a^2}{2r} \quad \text{and} \quad \frac{f_a - f_s}{f_s} \approx \frac{1 - a^2}{2r}$$

It can also be shown ([1] and [2]) that the crystal unit connected in series with a load capacitance C_L will have a composite resonance frequency f_L such that

$$\frac{f_L - f_s}{f_s} = \frac{C_1}{2(C_0 + C_L)} \qquad (8)$$

provided any stray capacitances are either neglected or included in C_0.

The equivalent circuits of figures 2a and 2b have exactly the same transadmittance characteristics; they differ only in the definition of values for the "stray" static capacitance values.

The circuit of figure 2c, however, does not take into account the presence of any shunt capacitance, and therefore will only serve to approximate the impedance of the device over a small frequency range near series resonance. Over this range

$$Z_{12} = R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) = R_1 + j(2\,\Delta\,\omega\,L_1) \tag{9}$$

which is exactly the same result one obtains if it is assumed that

$$2\,\Delta\,\omega\,L_1 << \frac{1}{\omega_s C_0}$$

in equation (3) above. In this case, the crystal reactance is:

$$X_c = 2\,\Delta\,\omega\,L_1 = 4\,\pi\,L_1\,(f - f_s).$$

Differentiating, $\frac{dX_c}{df} = 4\,\pi\,L_1$ (Ω/Hz), or

$$L_1 = \frac{1}{4\pi} \cdot \frac{dX_c}{df} \tag{10}$$

and L_1 may be directly determined from the slope of the reactance versus frequency function evaluated in the neighbourhood of f_s.

5 Parameters to be measured

Characterization of a crystal unit, therefore, requires determination of series resonance frequency, f_s; the motional resistance, R_1; the motional inductance, L_1 (or capacitance, C_1); and the three static capacitances, C_{13}, C_{23} and C_0. Other characteristics which are often specified are the derived characteristics:

- f_L: load resonance frequency; the frequency at which the series connected combination of crystal unit and a specified value of load capacitance will exhibit a resonant, zero phase condition;
- R_L-load resonance resistance; the real component of crystal unit equivalent impedance at frequency f_L;
- S-pulling sensitivity; the rate of change of f_L with changing load capacitance at a load capacitance C_L;
- $\Delta f_{L1,L2}$ pulling range; the difference between two load resonance frequencies corresponding to two specified values of load capacitance.

These characteristics are termed "derived" because they may all be calculated from the values of the shunt and motional parameters and the value of f_s. With suitable instrumentation they may also be measured with or without the introduction of physical capacitors into the measuring fixtures, as will be described below.

It is common practice to specify the resonance frequency f_r (frequency of zero phase) instead of series resonance frequency f_s. Generally, the difference between the two is negligible for fundamental mode units; however, when dealing with fifth and seventh overtone units, $f_r - f_s$ can be as great as several parts per million, and differentiation is necessary. f_s is the preferred parameter, as it is independent of stray capacitance effects. It is also necessary to be very specific about the definition of the "zero phase" condition: f_r is precisely defined as that frequency for which the transadmittance vector Y_{12} is purely conductive. This is not identical to the frequency at which the transmission in a test fixture exhibits zero phase shift, as the transmission phase shift depends upon the physical length of path between the test pins, and on the nature of the terminating impedances of the test pins. Again, the difference is small at lower frequencies, but can become significant for frequencies of 100 MHz or greater. At 100 MHz, for example, a matched line length of one centimetre results in a phase delay, $\Delta\Phi$ of about 0,02 radians; a resonator having $Q = 10\,000$ would exhibit a frequency error of

$$\frac{\Delta f}{f_s} \approx \frac{\Delta \Phi}{2Q} = 1 \times 10^{-6}$$

if the terminations are truly resistive. Consequently, great care is required in establishing the reference conditions when calibrating and adjusting real test fixtures and instruments.

6 Attributes of measurement systems

While a number of techniques have been described, and may be used, to obtain some or all of the network parameters described above, it seems appropriate to discuss first the general requirements for determination of the equivalent network parameters.

As noted above, one must determine both magnitude and phase of the admittance (or impedance) of the device at various frequencies in order to solve for the network parameters. Consequently, the measurement equipment shall permit calibration in terms of recognized standards of impedance and phase, and shall be equipped with means for frequency measurement. Today, many calibrated frequencies are broadcast, and it is a relatively simple matter to maintain a laboratory frequency source within 1×10^{-9} or better agreement with national standards.

Standards of phase and impedance, however, especially at frequencies above 100 MHz, are not easy to achieve, and generally can only be obtained in coaxial form, at impedances of 50 Ω or 75 Ω. Such standard impedances with traceable calibration to an accuracy of better than 1 %, and matched air lines with accurately known characteristic impedance and effective length (phase standards) calibrated to better than ±1 mm can be readily obtained. Short-circuit and open-circuit conditions can be established from first principles.

Reference impedance standards for use in fixtures based on other than 50 Ω or 75 Ω are not readily obtained, and require considerable effort to produce and calibrate.

Similarly, considerable ingenuity is always required to connect known impedances into test fixtures designed to accept the wire leads of crystal units without at the same time introducing additional stray reactances and extra line length.

With these general precautions in mind, we will examine some of the possible techniques for crystal measurement.

7 Active methods (oscillator or other closed-loop methods)

In principle, it is possible to construct a broad-band (or tuneable) active circuit which will sustain oscillations when a feedback loop is closed by inserting a crystal unit. The conditions for oscillation are well known: the net loop phase shift shall be $2n\pi$, $n = 0, 1, 2 \ldots$ and at equilibrium, net loop gain is unity. Such a circuit is shown in figure 5a, where a crystal unit or other impedance element completes the positive feedback loop by connecting between points 1 and 2. If the voltages at these pins, e_1 and e_2, have precisely the same phase, then a crystal unit connected in the circuit will control the frequency of oscillation at its resonance frequency, f_r. The oscillator sustaining circuit may be replaced by a tunable source and a phase detector as shown in figure 6 (where an automatic tracking arrangement is shown, but manual tuning may also be used) with the same result, i.e., the zero-phase frequency is determined. If the impedances presented by the test circuit at terminals 1 and 2 are accurately known, we can calculate the resonance resistance R_r of the device from knowledge of the amplitudes of e_1 and e_2, for example, using a vector voltmeter as in figure 5b. In this circuit, the frequency would be adjusted to give exactly zero phase between e_1 and e_2, and the resonance resistance found from the ratio of the magnitudes:

$$\frac{e_1}{e_2} = \frac{R_r + R_T}{R_T} \quad ; \quad R_r = \left(\frac{e_1}{e_2} - 1 \right) R_T \tag{11}$$

where R_T is the effective terminating resistance from test points to ground, while the value of f_r could be determined by measurement of the source frequency when the zero phase condition is satisfied.

If, however, there is any stray reactance appearing in shunt with the terminating impedances at points 1 and 2, both the frequency and the resistance determined above will be in error. The accuracy of this type of measurement depends upon the accuracy of the meter and the precision with which the circuit impedances can be realized. Repeatability of such a system will in general be quite good, so long as the same instruments and test fixtures are used, but the accuracy achieved (due to unavoidable stray reactances) will depend also on the motional parameters of the crystal unit being measured.

At this point, it should be noted that very little data are available to allow comparison of measurements between different measuring methods. Most "round robin" experiments have been restricted to comparison of results using equipments of the same kind at different locations.

Measurement of motional inductance/capacitance using the oscillator or transmission methods described above can in principle be accomplished in either of two ways. One method calls for the introduction of "known" values of capacitance in series with the crystal unit, and determining the change in frequency which results, as indicated by the connection of figure 5c, using equation (12) below. Adjusting frequency to the zero-phase point gives the load resonance frequency, f_L, and the load resonance resistance, R_L, directly. With this connection, it is very important that any stray capacitance to ground from the interconnection point between crystal unit and load capacitor be accurately known, and included in the effective value of C_L.

Because of the difficulty of determining these strays accurately, it is often easier to use two different values of C_L, using test-capacitor fixtures as nearly identical as possible so that all strays are essentially the same with each fixture. Then, the motional inductance is determined from equation (13) below:

The calculation of L_1 (or C_1) using a single load capacitance C_L is:

$$\frac{1}{\omega_s^2 L_1} = C_1 = \frac{2\,(f_L - f_s)\,(C_0 + C_L)}{f_s} \tag{12}$$

Using two load capacitances C_{L1} and C_{L2},

$$\frac{1}{\omega_s^2 L_1} = C_1 = \frac{2\,(f_{L1} - f_s)\,(f_{L2} - f_s)\,(C_{L2} - C_{L1})}{f_s\,(f_{L1} - f_{L2})} \tag{13}$$

In the case of two load capacitances (equation (13)), the value of C_0 is not required and only the difference between the load capacitance values is needed. Strays introduced by the test capacitor fixtures do not influence the result, so long as they are the same for the two fixtures.

The second method for determining motional parameters requires that, after the values of $f_r \approx f_s$ and $R_r \approx R_1$ have been determined using the circuit configuration of figure 5b, the phase adjuster setting is changed to produce two phase conditions between e_1 and e_2 voltages of opposite sign and equal magnitude, $\pm\Delta\Phi$ and the frequencies required for each phase condition are measured (f_1 and f_2). Knowing the test circuit impedances R_T, the motional resistance of the crystal unit R_1 and the series resonance frequency f_s, the motional capacitance C_1 (or inductance L_1) is calculated:

$$C_1 = \frac{1}{\omega_s^2 L_1} \approx \frac{(f_2 - f_1)}{f_s^2}\;\frac{\cot(\Delta\Phi)}{2\,(2R_T + R_1)} \tag{14}$$

This technique has the advantage that no additional stray reactances are introduced in making the measurement. However, especially when operated manually, the accuracy of the value determined depends directly on the accuracy with which R_T and R_1 are known and the accuracy of the phase shift value introduced. The motional parameters cannot be determined with any better accuracy than the network and crystal resistances known. Also, some additional error will be introduced due to the effects of the shunt capacitance C_0, which has been neglected in obtaining equation (14).

Probable accuracies obtainable with the above oscillator/transmission methods are considered to be about $\pm 1 \times 10^{-6}$ for f_r, ±5 % for R_r and ±8 % for L_1 and C_1, if reasonable care in calibration of the vector detector and in the fabrication of the test fixtures is exercised. At higher frequencies (above about 100 MHz), accuracy is degraded as unavoidable stray reactances become more significant. When measuring high order overtone crystals (seventh, ninth, etc.) it is not unusual to find that no zero-phase condition is possible.

All of the above oscillator and transmission methods can be operated without phase detection, but at reduced accuracy. When the oscillator method is used, an inherent phase condition is established, but unless a vector detector is used, the actual value of loop phase shall be suspect and the accuracy of the measurement is not well established. However, oscillator measurements can be very repeatable when the same equipment is used, making them very useful for use in manufacturing situations, as long as better means are used to assure the required accuracy and correlation with respect to standard methods of measurement.

Externally excited transmission circuits, when used without phase detection, determine the frequency of minimum impedance, f_m, rather than the resonance frequency, f_r. Since f_m lies below f_s by about the same amount that f_r lies above it, the accuracy is nearly the same; and in either case, it is well to keep in mind just what is being measured. However, when operated manually, it is more difficult to estimate the point of maximum transmission than to set the point of zero phase - this is not a consideration when computer-automated equipment is used, as curve fitting to measured points will allow very accurate interpolation to the precise frequency of the maximum.

Transmission test fixtures may be of the π-network type as described in IEC Publication 444, or of the T-network type as described in [12] and [13], as well as of other designs. In any case, the design and fabrication of the test fixtures are of critical importance, and correlation of results requires that all fixtures used shall be exactly alike.

8 Bridge methods

R.F. impedance and admittance bridges have been used for the measurement of crystal unit equivalent parameters in the vicinity of resonance [4]. Such bridges depend upon the calibration of the internal elements used in setting balance conditions, and are not easily standardized to available coaxial impedance standards especially at higher frequencies. Moreover, their use generally requires considerable care in adjustment, so that they are not well-suited for production measurements. Because of the limited reactance range of most commercially available bridges, load frequency and resistance measurements usually require the use of physical test capacitors placed in series with the device under test.

An automated microcircuit realization of a Scheering bridge [5] has been developed as an automatic crystal parameter measurement system. The details of this automatic system are beyond the scope of this guide. In general terms, it is based on a miniaturized bridge whose tuneable elements are varactor diodes, enabling electronic balancing of the bridge under control of a computer system. The details of this development have been published [7] and reported accuracies are very good.

An automatic measurement method based on a commercially available reflection coefficient bridge (impedance meter) has also been developed and reported [6]. This equipment has a coaxial measurement port, and is calibrated using standard 7 mm coaxial impedance elements, which can be readily obtained and easily certified by most national standards laboratories. Adaptors must be provided to permit connection of the wire leads of crystal units to the coaxial port, and their characteristics shall be accounted for when converting measured reflection coefficients to equivalent crystal parameters. Reported accuracy obtainable by this method is very good [6], [8]. Load resonance frequency and resistance can be determined by the phase offset method as described by Smythe [6], so that physical capacitor fixtures are not required - a significant advantage.

Since the reflection coefficient bridge is a single port system, one terminal of the crystal unit under test must be grounded, and it is not therefore possible to determine C_0, C_{13} and C_{23} separately with this system. They may be found from measurements made away from resonance with the enclosure grounded and ungrounded and lead connections reversed, if necessary.

For frequencies below the range of the reflection coefficient bridge (impedance meter), low frequency network analyzers are commercially available, having frequency capability from about 50 Hz to slightly above 10 MHz. These instruments measure the transmission characteristics of devices as two-port networks and calculate the equivalent series or parallel form of the trans-immittance parameters. They also permit determination of crystal load parameters by the phase offset method.

9 Automated network analyzer methods

Automatic two-port network analyzers have been developed for the general characterization of active and passive networks. These analyzers provide for the determination of the two-port scattering parameters of the network under test, and provide for correction of the measured responses to take into account imperfections in the equipment by referring network parameters to the impedance standards used to calibrate the equipment. A complete description of this type of equipment may be found in [9]. Commercial network analyzer/S-parameter instruments of this type are now available. For use as crystal measurement systems, stable synthesized signal sources shall be included in the system; some systems include such sources while others need to be modified for this use. Such systems provide for calibration at the measurement reference plane with coaxial impedance standards, and are capable of very accurate and reproducible measurements [10], [11]. The use of the scattering parameter methods, originally developed for application to microwave systems, allows for the separation of the trans-immittance parameters from the effects of shunt elements, so that the static capacitances C_{13} and C_{23} may be separated from the transmission characteristics and determined separately. Also, the test fixture imperfections are to at least to a first approximation removed from the measurement, as the "calibration" of the system is done at the measurement ports, and the error correction algorithms remove the effects of the system up to the reference plane from the measurements.

These automatic network analyzer systems have proved to be the most satisfactory way of obtaining precise measurements of immittance over very wide frequency ranges. Either one-port reflection measurements or two-port transmission measurements may be made as desired. For crystal unit measurements, the choice of one-port or two-port measurement is generally arbitrary, as the two yield essentially identical values for the motional parameters, differing only in the values of the static capacitances. As a guide, the following are general recommendations:

One-port measurements – Low resistance crystal units ($R_1 < 10\ \Omega$); crystal units for oscillator applications; situations where minimum measurement time is important.

Two-port measurements – High resistance crystal units ($R_1 > 100\ \Omega$); crystal units for filter use and some exacting oscillator applications; high frequency crystal units ($f_s > 100$ MHz).

Figure 7 shows the equivalent circuit of a crystal unit as connected for a one-port measurement and figure 8 shows the equivalent circuit of a crystal unit connected as a two-port device. The shunt capacitance C_0 of figure 7 includes the capacitances C_1 and C_2 of figure 8 in some combination (depending upon whether the enclosure is grounded or not) and thus differs from C_0 of figure 8.

The measured reflection response obtained for a one-port measurement is typified by figure 9, while figure 10 is a typical transmission response for a crystal unit in a two-port configuration.

A functional block diagram of the equipment required for the network analyzer method of measurement is shown in figure 11. The entire measurement and data reduction processes are controlled by computer programmes, so that operation is extremely simple, and measurement accuracy is essentially independent of operator skill.

10 Commercially available measurement systems

The instrument systems just described can all be used for the measurement of piezoelectric resonator parameters; however, many require some modifications such as improved signal sources, the addition of frequency counters or special detectors, etc. There are also available various measurement systems designed specifically for resonator measurement. These range from the manually operated "crystal impedance meter" test oscillators to special automated transmission measurement systems available from several manufacturers. Some of these are based on transmission networks electrically equivalent to that specified by IEC Publication 444, and use sophisticated computer-controlled synthesizers and vector detectors. Some such systems also include automatically controlled temperature chambers and switching networks to permit temperature testing of large numbers of units in batch mode.

The automated transmission test systems, shown in block diagram form in figure 12, with the capability of extensive mathematical data processing along with storage of measured transmission parameters during calibration with known impedances, provide better accuracy and repeatability than manually operated systems. These systems depend on the measurement of the output voltage of the test network, compared to the voltage of a reference channel. Considerable care is taken to isolate the reference channel from the test channel; however, the insertion impedance of the test device can only be obtained with respect to the assumed impedance of the reference resistors which are used to calibrate the system. These resistors are not coaxial devices and cannot be easily traced to national standards of impedance at high frequencies. Also, since the transmission parameters will be influenced by any shunt impedance between pins and ground, which cannot be separated without making other measurements, the accuracy of the derived parameters will be degraded, especially at higher frequencies. The use of several values of reference resistors permits modelling of the test fixture impedances, which reduces the requirement for fixture precision, and improves the precision of measurement over that which can be obtained with manual measurement systems or with oscillator methods.

Software and test fixtures specially designed for use with automatic network analyzer/scattering parameter systems are becoming commercially available. These software programmes are developed to operate with specific instruments and controllers and in some cases are available from the instrument manufacturers, while other programmes are furnished by third-party vendors. This availability has significantly reduced the cost of fully automated network analyzer systems for crystal unit measurements.

11 Comparison of the characteristics of various measurement systems

The various measurement systems described have some characteristics which are generally determined by the basic method employed. The following table gives a relative comparison of the basic methods with regard to these general characteristics.

Table 1 - Comparison of various quartz crystal unit measurement methods

Type of measuring system	Frequency range	Probable accuracy of frequency measurement	Ease of use	Relative cost in $
Vacuum tube CI-meters (obsolete)	8 kHz to 250 MHz	±5 to ±10 x 10^{-6}	Good	Low (only available on used market) (< 200)
Solid-state CI-meters	8 kHz to 250 MHz	±2 to ±5 x 10^{-6}	Good	Moderate (200 - 2 000)
Manual maximum transmission method (IEC Publication 302)	30 MHz max.	±2 to ±5 x 10^{-6}	Complex	Medium (~2 000)
Manual bridge methods	1 kHz to 200 MHz	±1 to ±5 x 10^{-6}	Complex	Moderate to high (2 000 - 20 000)
Automatic bridge methods	1 kHz to 200 MHz	±1 x 10^{-6}	Good	Very high (~40 000)
Locked loop zero-phase methods (IEC Publication 444-1)	1 MHz to 200 MHz	±1 x 10^{-6}	Good	High (20 000 - 30 000)
Computer-controlled zero-phase methods (IEC Publication 444-1)	1 MHz to 200 MHz	±1 x 10^{-6}	Very good (note 1)	Very high (~40 000)
Computer-controlled network analyzer methods (note 2)	1 GHz max.	±0,1 x 10^{-6} (note 3)	Very good	Very high (~35 000)

NOTES

1 The use of these systems is very easy, once suitable test software programmes are available. The design of such programmes can be involved and expensive. However, test software and special test fixtures for crystal unit measurements with automatic network analyzers are becoming commercially available.

2 Comparable precision can be achieved using transmission fixtures similar to the IEC π-network by use of computerized error correction methods.

3 As frequency increases above about 200 MHz, expected precision estimates will degrade due to problems in precise definition of the interface between test fixture and device, as well as the lower *Q* values of high frequency devices.

12 Parameter determination with automated *S*-parameter systems

The automatic network analyzer systems described obtain the scattering parameters of the device under test, fully corrected for system error terms. From these S-parameters, the admittance parameters of the device are calculated using standard transformations. The measurements are made at several frequencies around series resonance of the unit, so that an array of measurement frequencies and corresponding Y_{12}-data is obtained, from which the equivalent electrical parameters may be estimated. One method of estimation is by means of an iterative non-linear least squares method [11] which directly calculates the "best fit" values for R_1, L_1, C_1 and C_0. If C_{13} and C_{23} are also required, the Y_{11} and Y_{12} admittance parameters are also needed from the measurement. There are several different approaches for non-linear least squares estimation, including the variable metric method [11], which converges rapidly but requires calculation of both first and second derivatives at each frequency; the Gauss-Newton method, which converges much more slowly; and the Marquardt method of steepest descent, which uses first derivative information only. For any of these iterative methods, it is necessary to obtain good initial estimates of the parameters if reliable and rapid convergence is to be assured. Initial estimates can be obtained with one of the linear methods below. Depending on the need for precision, and the importance of rapid measurement, the linear methods may provide adequate results without further processing.

If only the motional parameters are needed (R_1, L_1 and f_s), these may be obtained from the real component of Y_{12} (i.e. G_{12}) in the following manner [10]. The expression for G_{12} is from equation (3):

$$G_{12} = \frac{R_1}{R_1^2 + \left[4\pi(f - f_s)\, L_1\right]^2}$$

The reciprocal of this expression then is:

$$E = \frac{1}{G_{12}} = R_1 + \frac{(4\pi L_1)^2}{R_1}\,(f - f_s)^2 \qquad (15)$$

which has the following properties:

a) a minimum value of R_1 at $f = f_s$;

b) $\mathrm{d}E/\mathrm{d}f$ is zero at $f = f_s$;

c) when f_s and R_1 are known, L_1 can be determined from the coefficient of the $(f - f_s)^2$ term.

Consequently if the reciprocals of the G_{12} values are calculated and fitted to a quadratic function of frequency, f_s is found directly as the value of f for which the first derivative of the function is zero. Evaluating the function at this value of f then gives the value of R_1 directly:

$$E = K_1 + fK_2 + f^2K_3 \tag{16}$$

Series resonance frequency is:

$$f_s = -\frac{K_2}{2K_3}$$

Substituting this value for f in the expression for E above, R_1 is:

$$R_1 = K_1 - \frac{K_2^2}{4K_3}$$

It should be noted that in the presence of a shunt conductance term G_0 the value of R_1 will be in error.

Equating the coefficients of the f^2 terms in equations (15) and (16) above, the value of L_1 may be calculated as:

$$L_1 = \frac{1}{4\pi} \sqrt{K_3 R_1}$$

and C_1 may be calculated from the defining equation

$$C_1 = \frac{1}{L_1 \omega_s^2}$$

Since C_0 is not contained in the theoretical expression for G_{12}, no estimate of C_0 is obtained from this analysis.

The advantage of this method of estimating the motional parameters is that it is very fast, requiring few calculations. It has the disadvantages that accuracy is degraded if points lying further than about one Q-bandwidth from series resonance are included in the calculation, and it is quite susceptible to error in the presence of random noise in the measured data. A much more robust linear method makes use of both real and imaginary components of the transadmittance data. This method makes use of a linear least squares technique to fit a circle in the Y-plane to the measured Y_{12}-points, and then uses the measured data to obtain the reactance as a function of frequency to allow estimation of series resonance frequency and inductance, as described below.

The derivation of motional parameters from two-port measurements is illustrated in figure 14. First, the corrected transadmittance values

$$Y_{12} = G_{12} + jB_{12}$$

are calculated at each frequency of measurement, and the transimpedance vectors are calculated as:

$$Z_{12} = \frac{G_{12}}{G_{12}^2 + B_{12}^2} - j\frac{B_{12}}{G_{12}^2 + B_{12}^2} = R_s + jX_s$$

The values of R_s and X_s are plotted in figure 14, and the solid curves represent least-squares fitted polynomial functions fitted to the data points. (To avoid computational difficulties, the frequency co-ordinates are transformed by subtracting a constant value approximately equal to the resonance frequency.) Resonance frequency, f_r, is then determined at the intercept of the smoothed X_s function on the zero reactance axis. The resonance resistance, R_r, is the value of the smoothed R_s function at this value of the frequency co-ordinate.

To obtain values of f_s, L_1 and R_1 a circle in the Y-plane is fitted to the measured Y_{12} values; this circle will be centred at the point

$$G_c = G_0 + \frac{1}{2R_1}, \quad B_c = \omega_s C_0$$

The measured data points are then translated along radii to lie on the fitted circle to smooth the data effectively. (This is a tacit assumption that random errors in each measured component are equally probable.) Then, using the "smoothed" values (after being translated to lie on the fitted circle) B_0 is subtracted from each susceptance component, thus mathematically removing C_0 effects from the data.

After removing C_0 effects, the new admittance vectors will represent only the motional arm parameters. Transformation to the Z-plane results now in a constant real component $R_s = R_1$. The X_s component will now be essentially a straight line over a relatively wide frequency range, intercepting the zero reactance axis at f_s, and having a slope

$$dX_s/df = 4\pi L_1$$

with the accuracy of the narrow band approximation.

These calculations are performed mathematically by the computer, but the graphical representation illustrates the method.

The load parameters, f_L and R_L, can be calculated from the motional parameters and the value of C_0; however, for small values of C_L particularly, the accuracy of this extrapolation may not be adequate. With the network analyzer, additional measurements can be made in the frequency range at which the insertion reactance of the crystal unit is approximately equal to the magnitude of the load capacitor reactance, and the load parameters can then be interpolated quite accurately. To accomplish this without the use of a special test fixture, the approximate load resonance frequency is calculated using the f_s, C_1 and C_0 parameters already determined. Then, measurements are made at several frequencies near this value, and the Z_{12}-vectors calculated at each frequency. The resistive and reactive components are then fitted to polynomial functions of frequency as before, as shown graphically in figure 15. The "smoothed" reactance function is used to interpolate the precise value of f for which X_s is precisely equal to the magnitude of the reactance of the specified load capacitor, giving an accurate value of f_L. The R_s function is then evaluated at this value of f to obtain an accurate measure of R_L.

The smoothed X_s function may then be used to calculate several paired values of load frequency and load capacitance over a range of ±10 % of the specified C_L value. From these, a polynomial function relating frequency to load capacitance can be formed by a least squares method,

$$f_L = K_1 + K_2 C_L + K_3 C_L^2 + K_4 C_L^3$$

and the pulling sensitivity, S, calculated as the derivative of this function

$$S = \mathrm{d}f_L/\mathrm{d}C_L = K_2 + 2K_3 C_L + 3K_4 C_L^2$$

and may be evaluated for the specified load capacitance, as well as for other values within the data range. (Extrapolation beyond the range for which data were obtained is always dangerous!).

It must be kept in mind that load resonance parameters cannot be isolated from the influence of C_0, including any stray capacitances introduced by wiring paths, etc. These strays will include the C_{13} and C_{23} values of the crystal unit as well as any strays from the circuit being used. It is the responsibility of the circuit designer to establish the total effective C_L value for his application. It is often useful, for this reason to obtain the f_L, R_L and S load parameters at several C_L values, such as ±0,5 pF, ±1,0 pF and ±1,5 pF different from the specified value.

All of these parameters may also be determined from one-port measurements as well, bearing in mind that the C_0-parameter is different with the one-port connection.

13 Precautions for making precise measurements

When the best possible estimation of the equivalent circuit parameters is desired, special attention shall be given to avoiding environmental effects which can have a very significant influence on the results. These include the temperature, temperature gradients, drive level, and characteristics of the test fixture, as discussed below.

13.1 *Thermal effects*

The frequency, resistance and motional impedance of a crystal unit all depend to some degree on the temperature and the rate of change of temperature of the unit during the measurement. In addition, since parameters are estimated from a series of measurements at several frequencies near resonance, it is especially important that the unit should not be disturbed during the process of obtaining these measurements as any drift would distort the best-fit estimation function. In addition, if close correlation of results obtained at different times is desired, it is important that the measurements be made at precisely the same temperature or that the temperature coefficients of the parameters be accurately known so that all measurements can be corrected to a common temperature value.

Minimizing thermal gradient effects requires that all the units to be tested, the test fixtures and the instruments be allowed to reach equilibrium with the environment of the test room before attempting to make measurements. In addition, crystal units should be handled with plastic tweezers or other non-conducting means to avoid heating by finger contact. Protection from air currents, heat sources and small fluctuations in room temperature can be provided by placing a relatively massive shield over the unit when it is installed in the test fixture. The temperature of the unit during test can be determined by monitoring the temperature of this shield with a precision thermometer if sufficient time has been allowed for equilibrium to be reached. An accuracy of better than 0,1 °C is required if frequency correlation to within better than $0{,}05 \times 10^{-6}$ is needed, as it is not unusual for a crystal unit to exhibit frequency changes as great as $0{,}5 \times 10^{-6}$ per degree.

Because of this sensitivity, special crystal units having very low temperature coefficients of frequency near room temperature are advisable for correlating measurement equipment in the factory.

13.2 *Drive level effects*

It has been widely observed and reported that the parameters of quartz crystal units, especially frequency and resistance, depend on the level of excitation. The effects are approximately proportional to the square of the drive current, so that precision measurements should ideally be made at low drive levels. For thickness shear modes, a test current of no more than about 200 µA or 300 µA r.m.s. is usually satisfactory, while low-frequency flexure types may require levels as low as 10 µA. Also, if measurement results are to be repeated at different times, it is necessary that all measurements be performed at essentially the same drive level.

13.3 *Test fixture considerations*

Most crystal units are equipped with either radial lead wires extending from one surface of the enclosure, or with metallic pads on one surface for "surface mounting" to the equipment. Unfortunately, neither of these configurations is compatible with the coaxial connectors usually found on r.f. test equipment so that some kind of adapting test fixture is needed. The crystal unit measurements can be no more accurate than the characterization of the test fixture itself. If an automatic network analyzer method is used, the fixture up to the reference plane will be included in the calibration of the equipment, and the main requirement is that the system as calibrated remains unchanged during the measurement.

One point to consider especially for high frequency measurements is the added capacitance and inductance that might be introduced at the connection between crystal leads and the test fixture due to excess lead length of the crystal unit. To eliminate this problem, the test fixture connector should be a hollow conductor so that any excess lead wire can extend within the connector pin. Also it should be possible to calibrate the system with known impedances which do not disturb the character of the reference plane. If the measurement is to be "traceable" to national standards, the reference impedances shall be certified from first principles, such as short or open circuits, or they shall be equipped with coaxial connections or other adapters which are certified by a standards laboratory. Test fixtures and calibration standards which meet these requirements are now commercially available.

13.4 *Transients in the measuring system*

When measuring crystal units it should be recognized that transient behaviour will occur, when excitation frequency is changed in both the instrumentation (such as the settling time for a synthesizer after a frequency is programmed or the time required for a switch closure to become stable or the time required for a detector to reach a stable indication), and in the device itself. The latter may well be the longer time, particularly for low frequency or high Q devices.

The behaviour of the crystal unit response immediately after a step change in excitation frequency has been made can be explained as consisting of two simultaneous transients. First, the initial frequency signal will decay with a time constant proportional to the ratio Q/f, and at the same time the new frequency signal will build up with a similar time constant. While both signals are present, transient behaviour of both amplitude and phase of the response will be observed, so that valid data representing the behaviour at the new frequency will be obtained only after waiting for the transients to decay adequately.

Figures 16 and 17 show a simulation of the response of a crystal unit connected in a 50 Ω transmission system. It is assumed that the initial frequency was stabilized, and at time $t = 0$, the synthesizer was set to a new frequency without any discontinuity of either amplitude or phase - a "perfect" synthesizer. The time scale has been normalized to units of Q/f_s of the crystal unit, as these are values which would normally be known approximately for a crystal unit being measured. The horizontal lines represent deviations from the final steady state response of ±0,5 % amplitude and ±0,5° phase, which are considered to be the minimum accuracy required for a precision measurement. Figures 18 and 19 are similar plots for a crystal unit having very different parameters; in terms of Q/f_s, however, the settling time required is about the same. It is clear that instrument switching time and settling time as well as device settling time shall all be taken into consideration in the measurement programme.

14 Measurement methods in the production environment

Test and measurement of crystal units in a production facility pose some specific problems. Generally, high throughput is required and devices are checked against specified tolerances on a "go" or "no-go" basis. In most cases not all parameters are specified, and therefore testing may be limited to include only those specified parameters together with any additional measurements needed to assess the general quality of the product. Obviously, all devices need to be tested against specified parameter value tolerances; quality assessment, however, may be implemented on a sampling basis, especially if production quantities are large.

The equipment used for production testing can be selected on the basis of device requirements; i.e. if only frequency and resistance are specified, then relatively simple oscillator or transmission test facilities are adequate. The degree of automation of the test equipment will depend upon the quantity of product involved. The advantages of higher capacity and better reproducibility of data resulting from automated testing are usually sufficient justification in themselves. When some portion of the product requires measurement of L_1 (C_1) values, and/or determination of load parameters, f_L, R_L and S_L, the one- or two-port S-parameter equipments will provide relatively fast measurement of all parameters without the need for additional test fixtures, and therefore will be a good choice. The one-port reflection equipment requires less measurement time than two-port systems but has other limitations, as previously discussed. The automated transmission type equipments are particularly suited to applications requiring temperature testing of devices.

Regardless of the test methods chosen for the production floor, it is advisable that at least one system be available which will permit complete characterization of a device, with measurements referred to acceptable, traceable impedance and phase standards. With this system, checks of calibration and accuracy of the production test equipment can be regularly conducted, and/or sampling tests of production units may be carried out to track, on a statistical basis, both the product performance and the validity of the production test equipment. The key to success is a regularly scheduled "calibration" of the production test equipment in terms of transfer standards which are referenced to the standard system, which, in turn, is calibrated to traceable impedance and phase standards.

15 Conclusion

In summary, the complete characterization of the static and motional equivalent electrical parameters of quartz crystal units is not a trivial undertaking. Several possible methods of measurement have been described in general terms, and brief descriptions of data reduction methods given for those automated systems offering the best obtainable accuracy and precision.

Very little has been said here about the very significant problem of providing adequate test fixtures, nor have the questions of temperature-testing, unwanted mode scanning, and use-circuit characterization been addressed here. These questions present as much difficulty as the selection of basic measuring methods and need to be carefully considered in practice.

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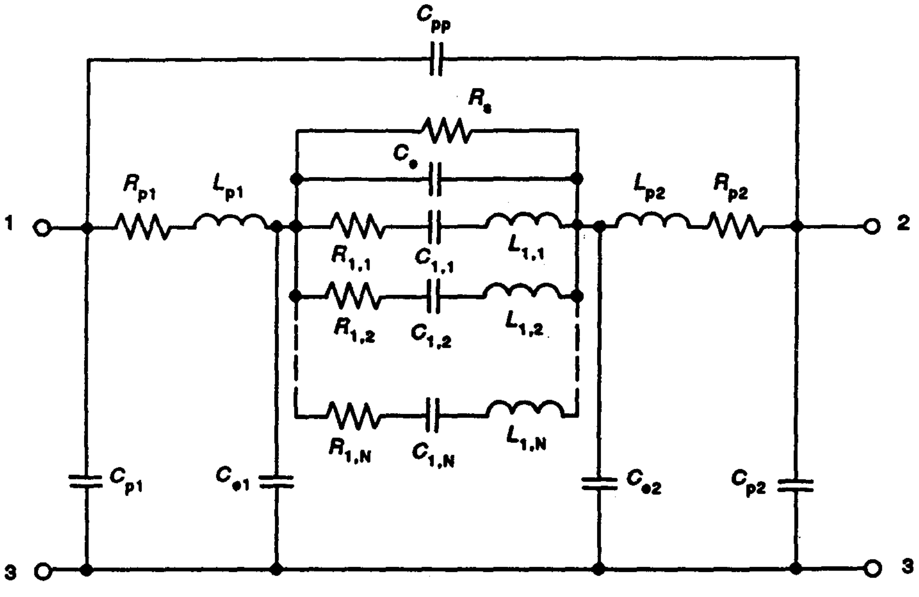


NOTE – This network is valid up to 350 MHz.

Figure 1 - Nearly exact equivalent electrical network of a piezoelectric quartz resonator

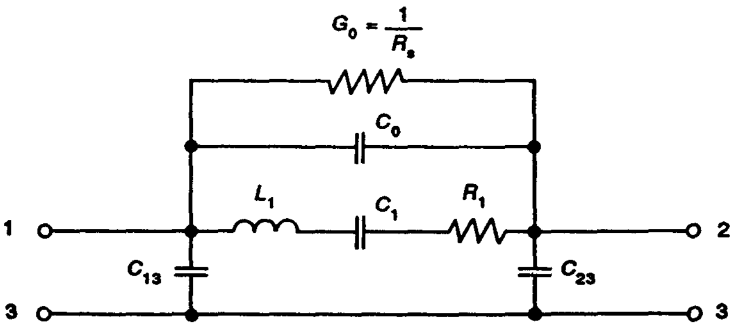
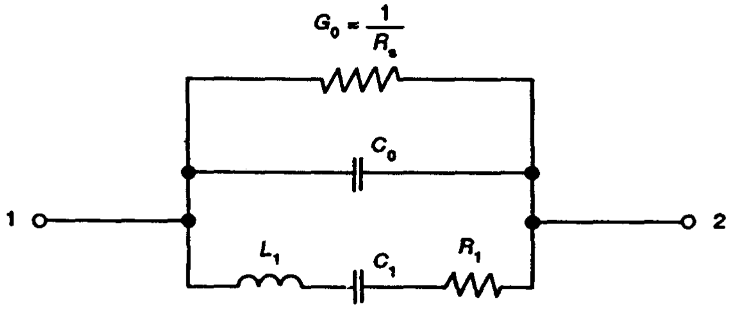


Figure 2a - Equivalent network adequate for most applications. Three-terminal, two-port model suitable over a bandwidth of ± a few percent from $\omega_s = 1/\sqrt{L_1C_1}$



NOTE - This network is valid up to 200 MHz.

Figure 2b - Two-terminal representation when enclosure is not grounded. C_{13} and C_{23} are included in the C_0 value

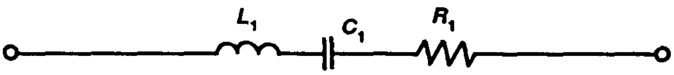


Figure 2c - Simple two-terminal equivalent network, useful over very narrow bandwitdh when C_0 may be neglected

Figure 2 - Simplifications of the equivalent electrical network

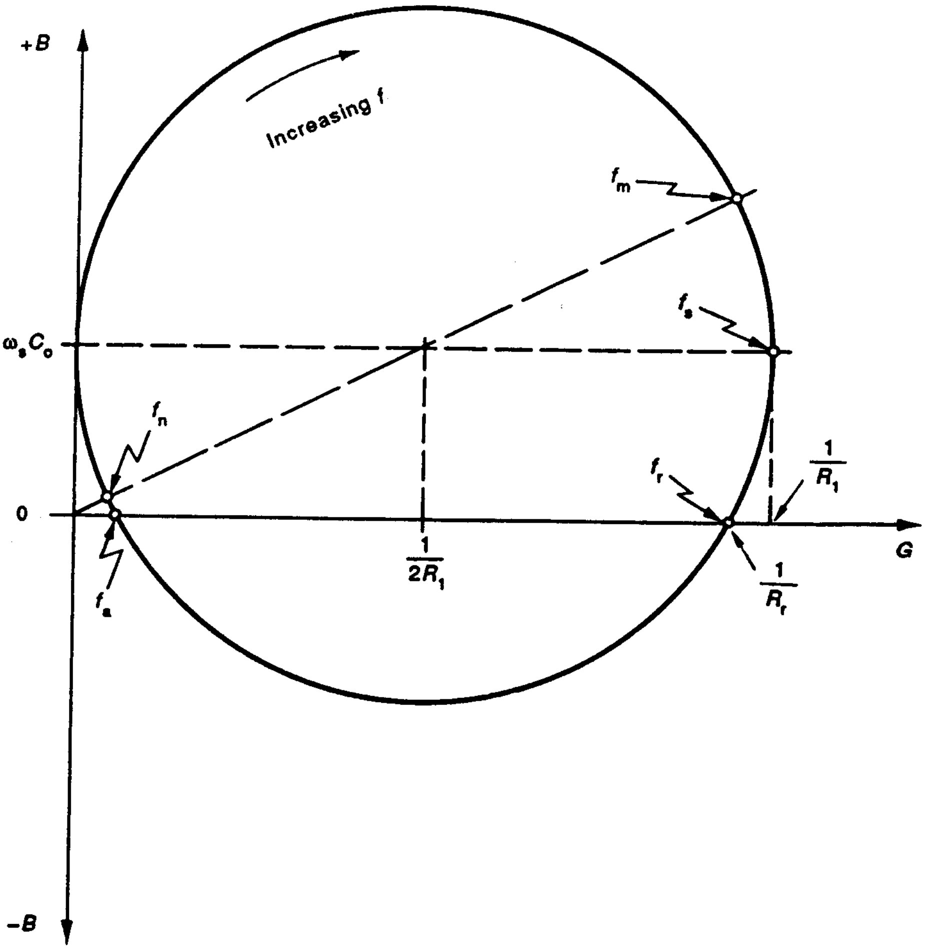


Figure 3 - Locus of a crystal unit transadmittance function in the Y-plane (when no shunt conductance G_0 is present) showing the points corresponding to the five characteristic frequencies

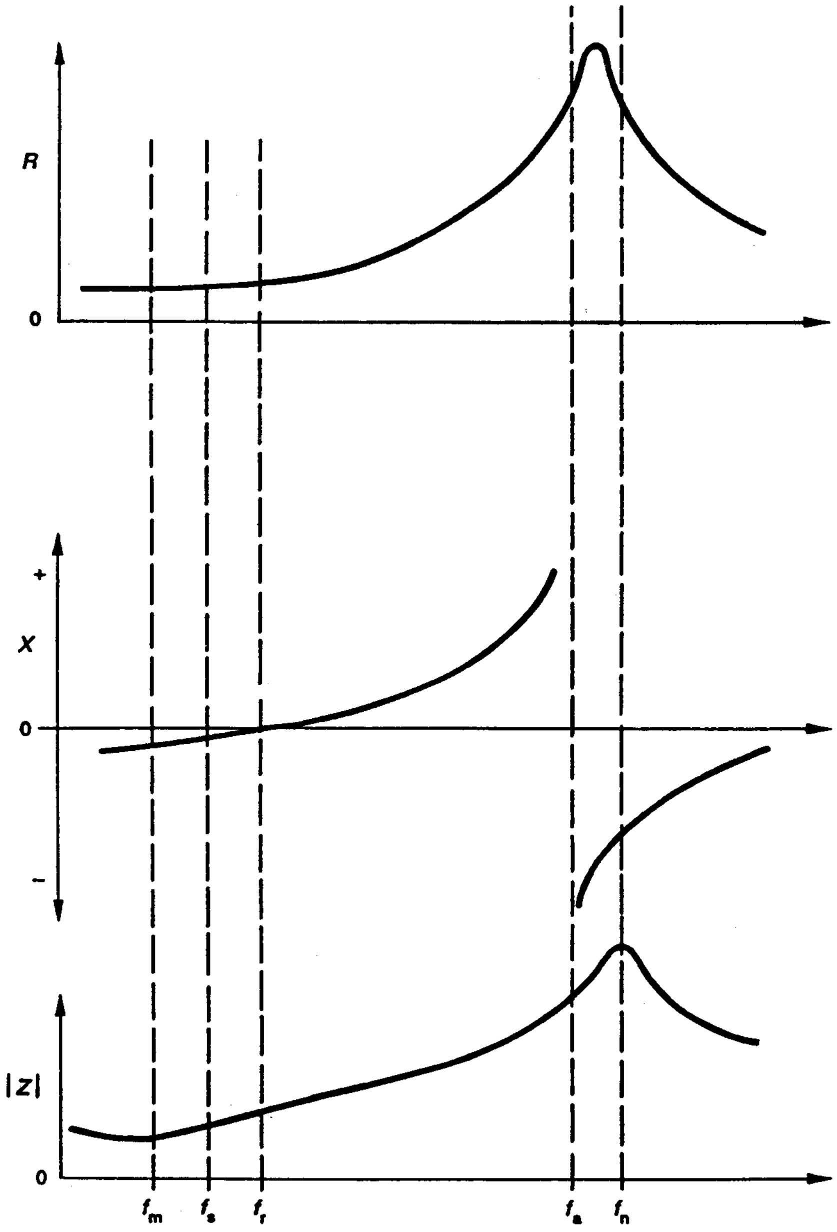


Figure 4 - Impedance versus frequency characteristics of a quartz crystal unit near resonance

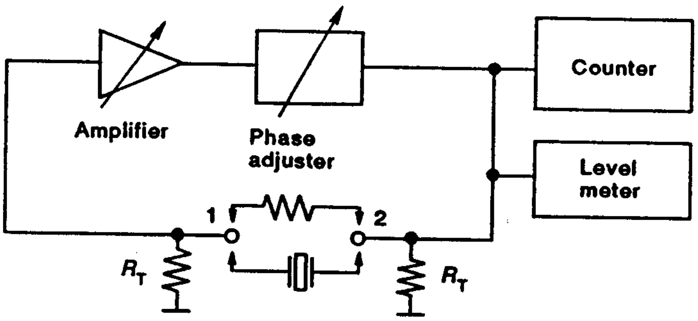


Figure 5a - Oscillator test circuit for crystal units (f_r and R_r)

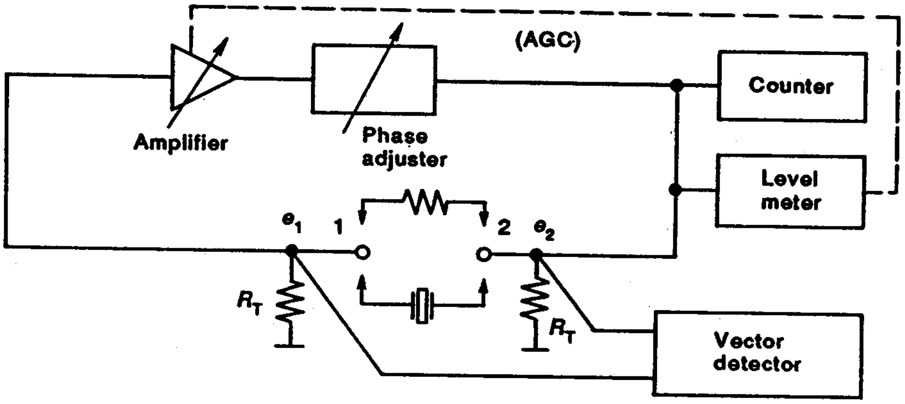


Figure 5b - Modifications to oscillator method for improved accuracy and precision

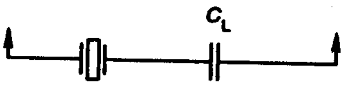


Figure 5c - Determination of f_L and R_L requires test fixture with added series capacitor

Figure 5 - Some possible oscillator test circuit configurations for crystal resonator measurements

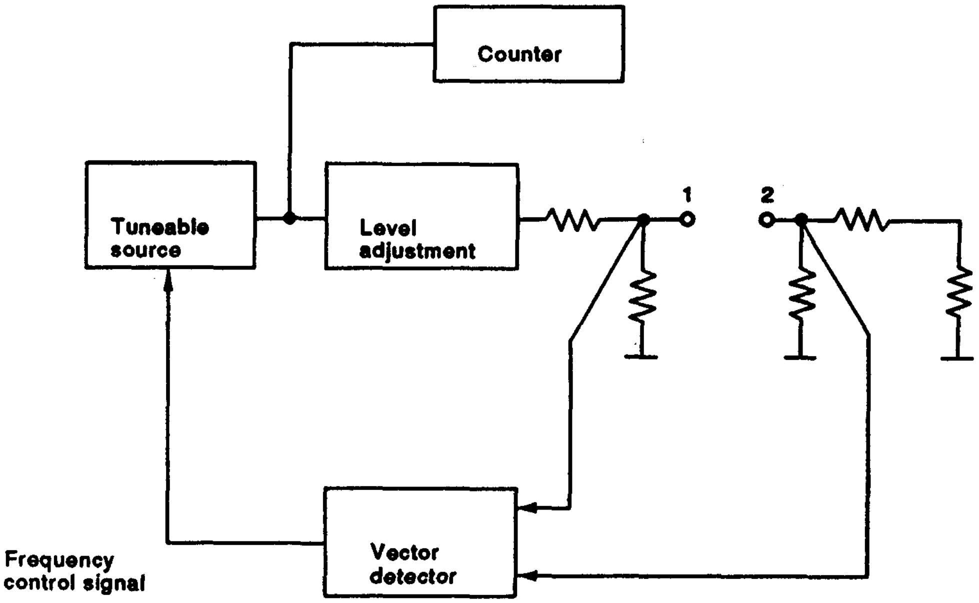


Figure 6 - Transmission measurement method for crystal resonators

For a single-port measurement (reflection), the equivalent circuit is as shown in figure 7.

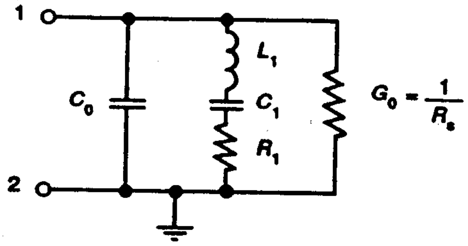


Figure 7

For a two-port measurement on a single resonator, the circuit is as given in figure 8.

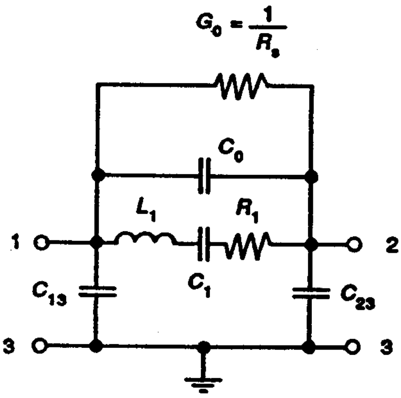
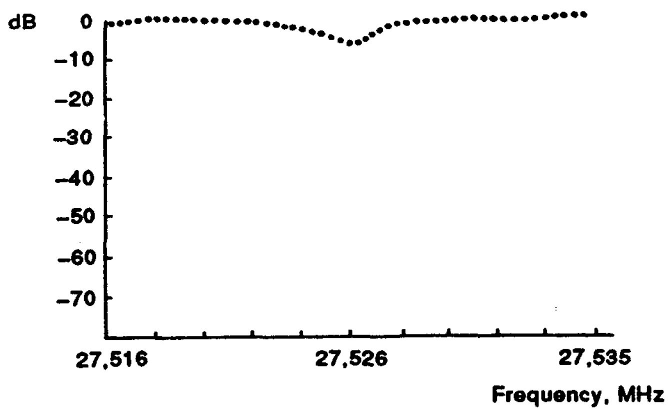


Figure 8



Number of calibration frequencies:	100
Frequency point file:	F5-600
Error parameter file:	ER5-600
Calibration date:	16 July 1984
Measurement demo:	16 July 1984
Crystal No.:	#37
Temperature:	23,2 °C
Start frequency:	27,516000 MHz
Stop frequency:	27,536000 MHz
No. of measured frequency points:	100
Result calculated using one point in:	5
Synthesizer level:	− 4,0 dBm

Frequency (MHz)	C_0 (pF)	R_m (Ω)	L_m (mH)	C_m (pF)	Q	P (µW)
27,5262301	3,19	15,61	2,7948	1,19617E-02	30957	9,19

ΔF (Hz) = 0,000

ΔC_0 (pF) = 0,494

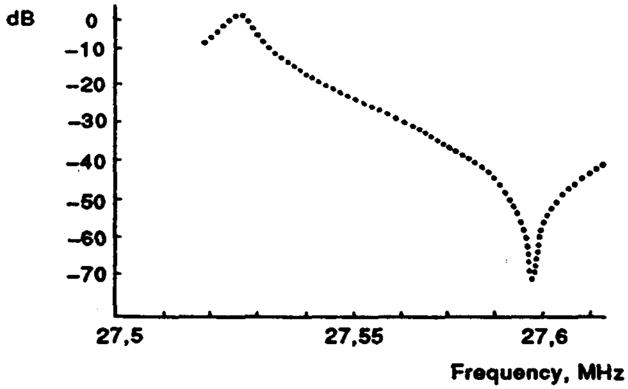
ΔR_m (Ω) = 0,515

ΔL_m (mH) = 0,00000

Load resonance frequency:
$f(20)$ = 27,533329 MHz
$f(30)$ = 27,531190 MHz

Pulling sensitivity:
$S(20)$ = −11,1206 1*E-6/pF
$S(30)$ = − 5,4291 1*E-6/pF

Figure 9 - Reflection measurement



Number of calibration frequencies:	100
Frequency point file:	F5-600
Error parameter file:	ET5-600
Calibration date:	16 July 1984
Measurement demo:	16 July 1984
Crystal No.:	#37
Temperature:	23,2 °C
Start frequency:	27,500000 MHz
Stop frequency:	27,600000 MHz
No. of measured frequency points:	100
Result calculated using one point in:	5
Synthesizer level:	–0,3 dBm

Frequency (MHz)	C_0 (pF)	R_m (Ω)	L_m (mH)	C_m (pF)	Q	P (µW)
27,5263940	2,56	15,77	2,9118	1,14810E-02	31934	6,98

ΔF (Hz) = 0,017 ΔC_0 (pF) = 0,022 ΔR_m (Ω) = 2,135 ΔL_m (mH) = 0,00002

Load resonance frequency:
$f(20)$ = 27,533400 MHz
$f(30)$ = 27,531248 MHz

Pulling sensitivity:
$S(20)$ = –11,2833 1*E-6/pF
$S(30)$ = – 5,4162 1*E-6/pF

Figure 10 - Transmission measurement

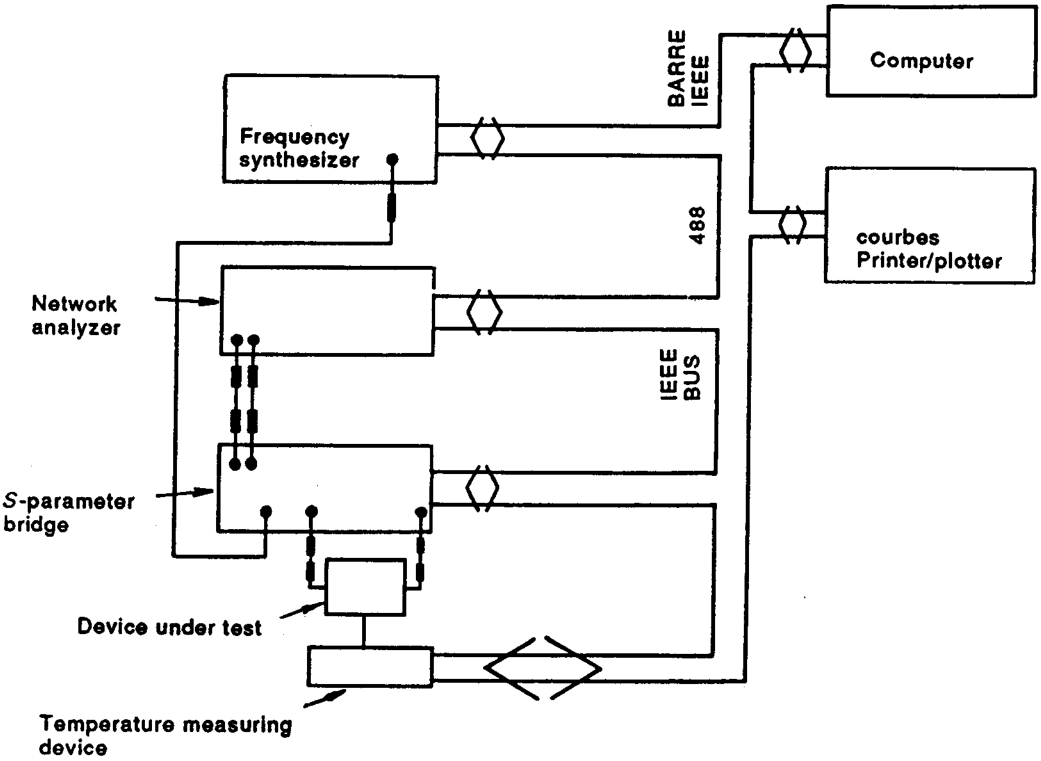


Figure 11 - Instrumentation block diagram

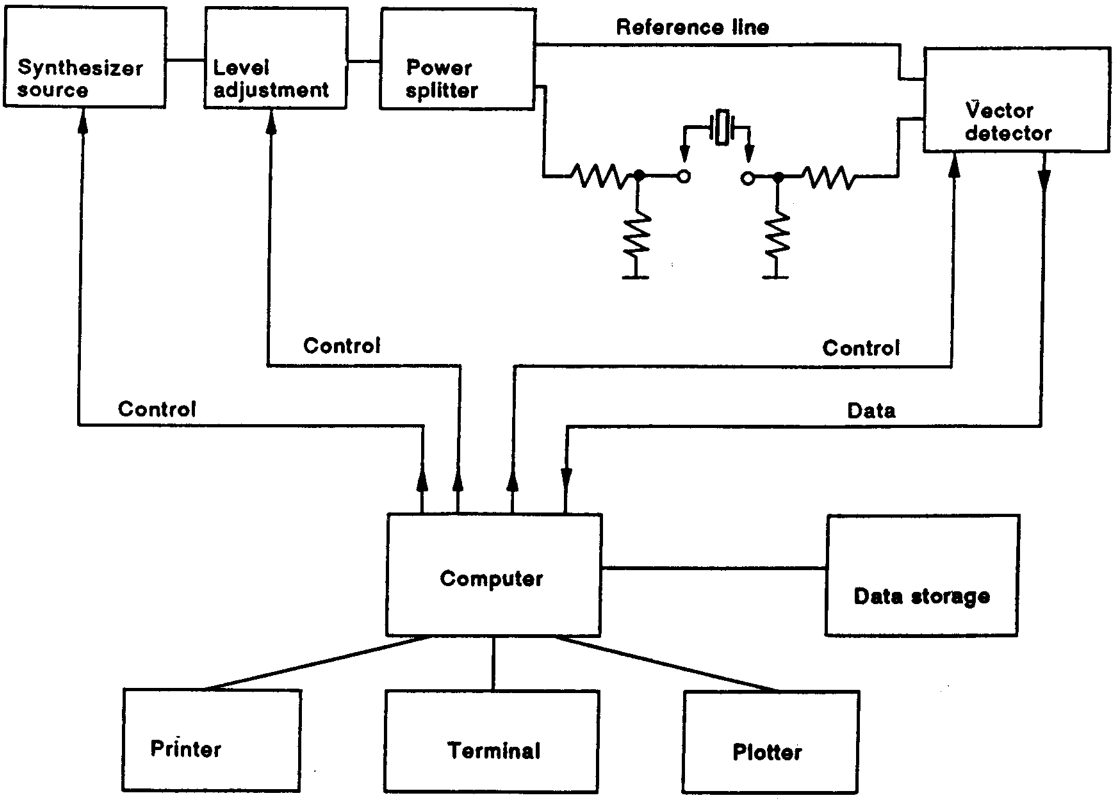


Figure 12 - Automation of the transmission measurement method

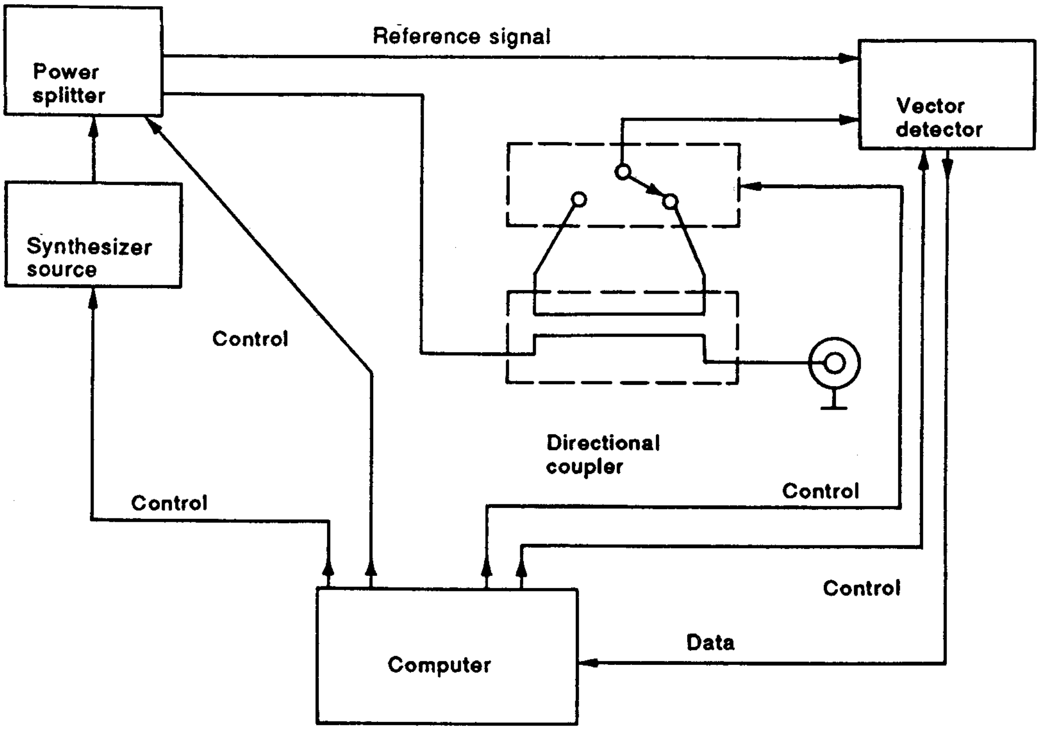
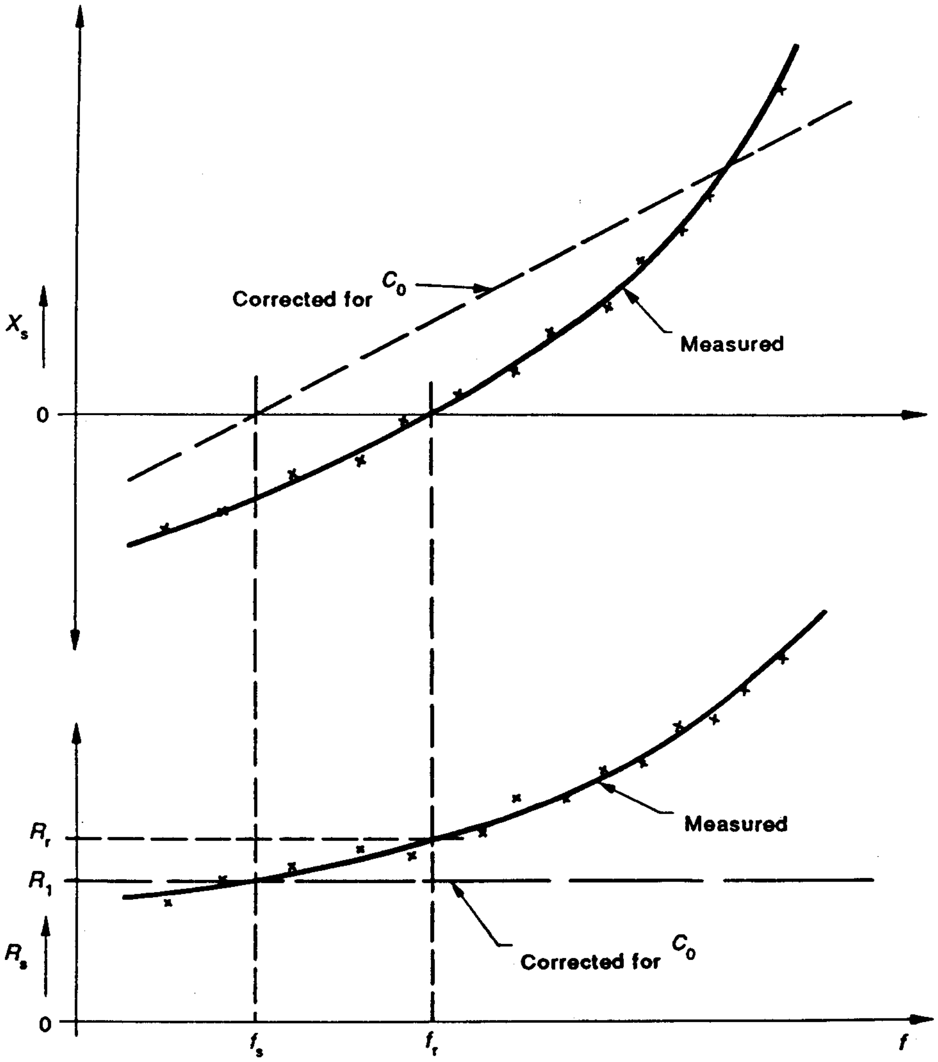


Figure 13 - Automatic reflectometer impedance measurement method



Measured $Y_{12} = G_{12} + jB_{12}$

Corrected for C_0, $B'_{12} = B_{12} - \omega_s C_0$

and $Y'_{12} = G_{12} + jB'_{12}$

Fitted polynomial interpolation functions provide data smoothing.

Figure 14 - Derivation of motional parameters from transadmittance measurements

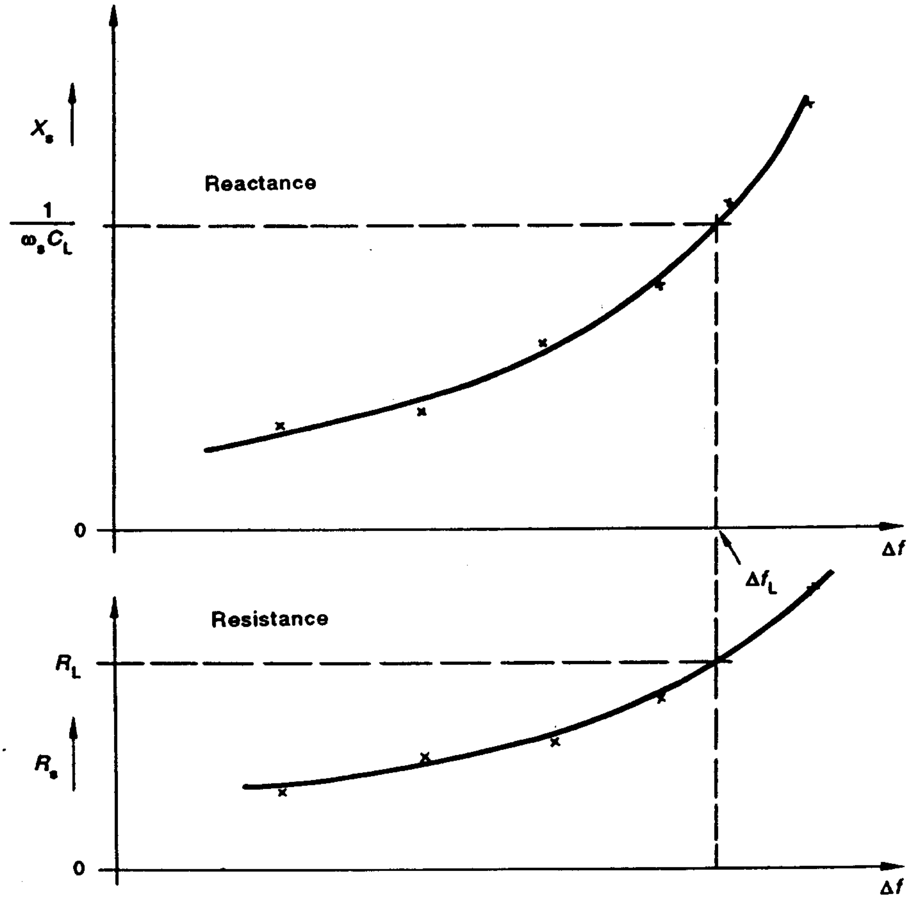


Figure 15 - Derivation of load parameters from measured transadmittance above resonance:

$$Z_{12} = \frac{1}{Y_{12}} = \frac{G_{12}}{G_{12}^2 + B_{12}^2} - \frac{j B_{12}}{G_{12}^2 + B_{12}^2} = R_s + j X_s$$

Fitted polynomial interpolation functions provide data smoothing.

Resonator f_s (kHz) = 5 000,085
Resonator Q = 2 500 000
Initial frequency from f_0 (H:) = –2,000
Frequency step (Hz) = 2,10
(Q/F), seconds = 0,26190

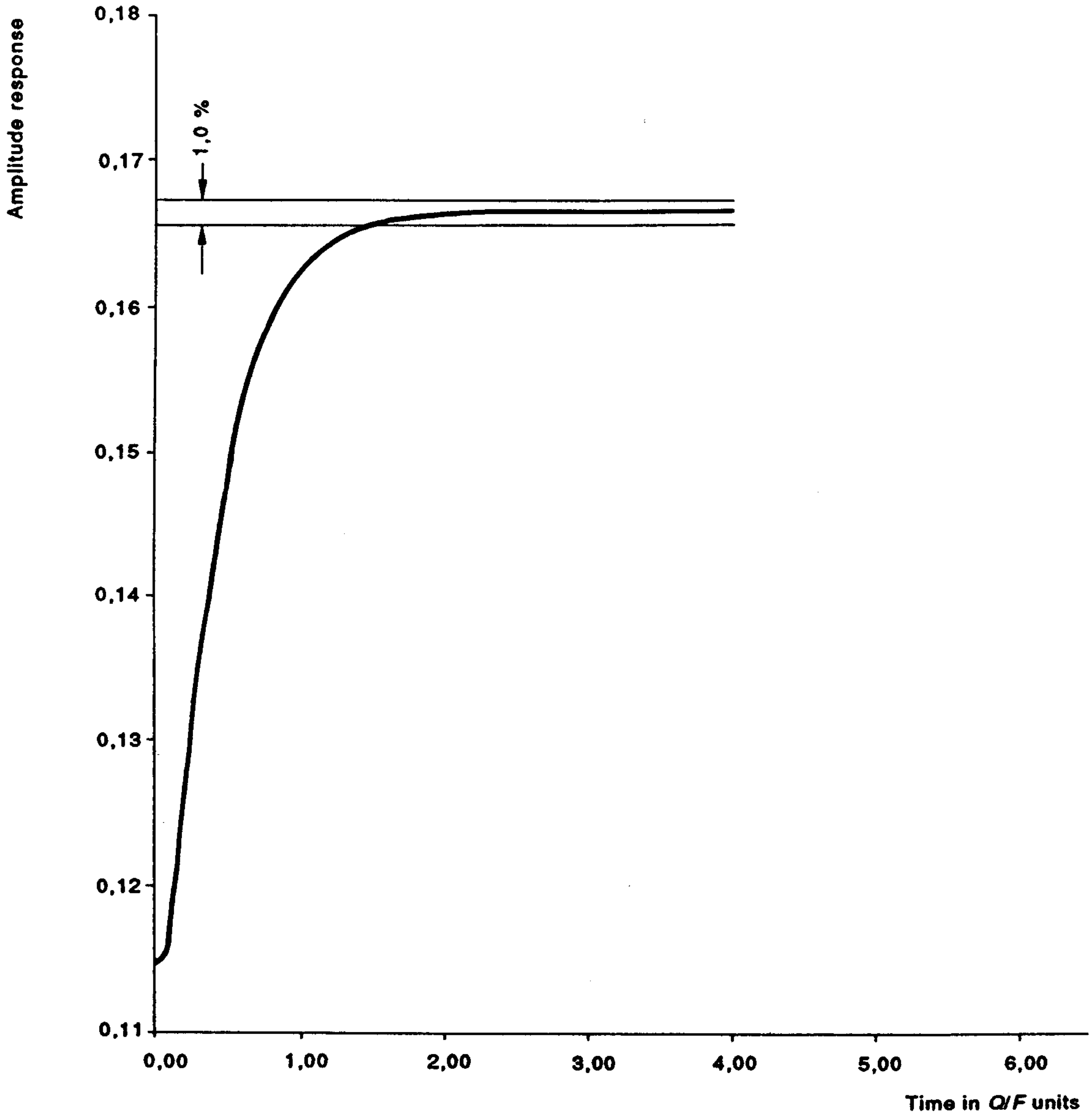
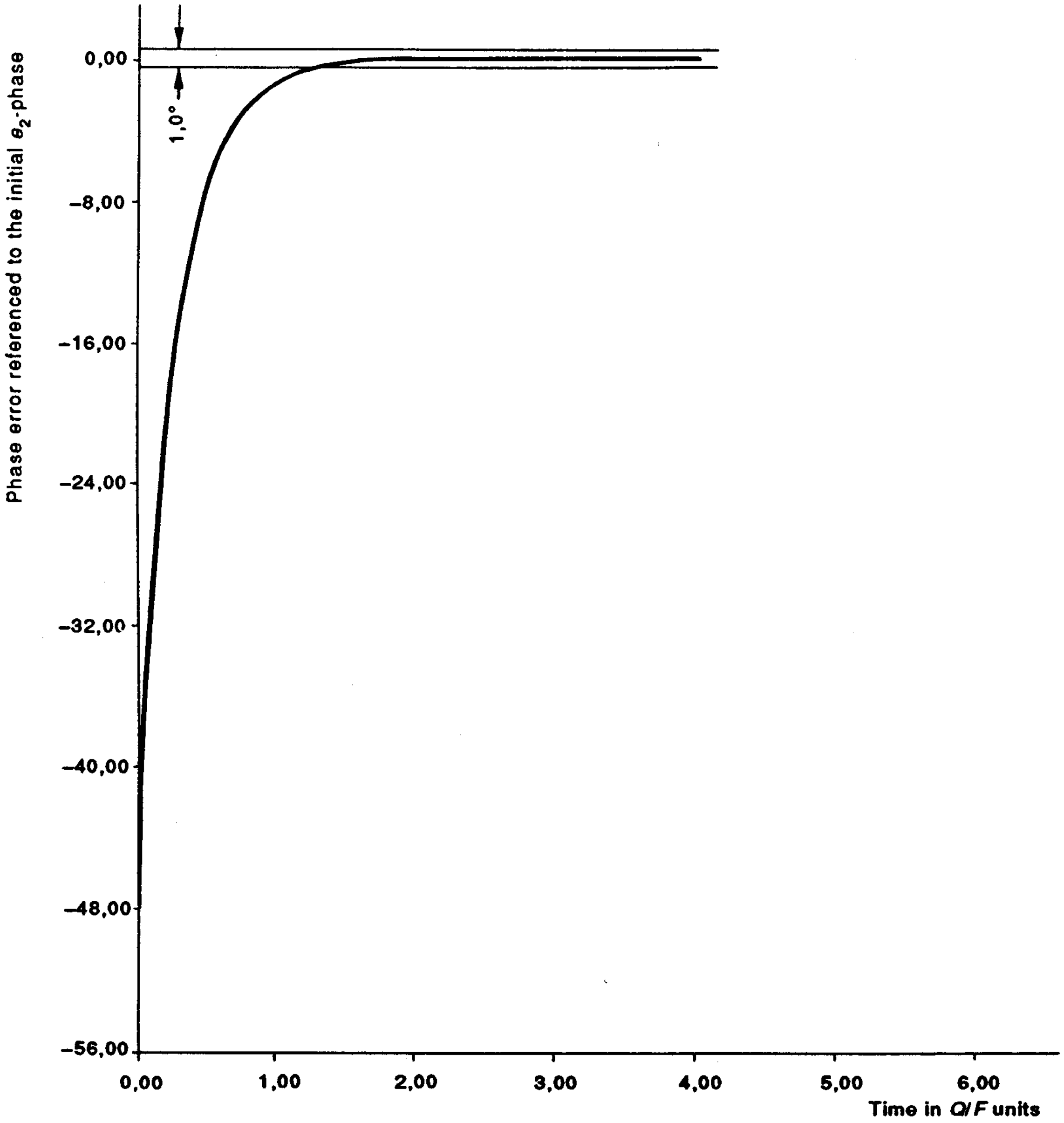


Figure 16 - Amplitude response of 5 MHz, 5th overtone resonator in 50 Ω system



Resonator f_s (kHz) = 5 000,085
Resonator Q = 2 500 000
Initial frequency from f_0 (H:) = –2,000
Frequency step (Hz) = 2,10
(Q/F), seconds = 0,26190

Figure 17 - Phase response of 5 MHz, 5th overtone resonator, in 50 Ω system

Resonator f_s (kHz) = 75,565
Resonator Q = 120 000
Initial frequency from f_0 (H:) = −0,500
Frequency step (Hz) = 0,50
(Q/F), seconds = 0,68059

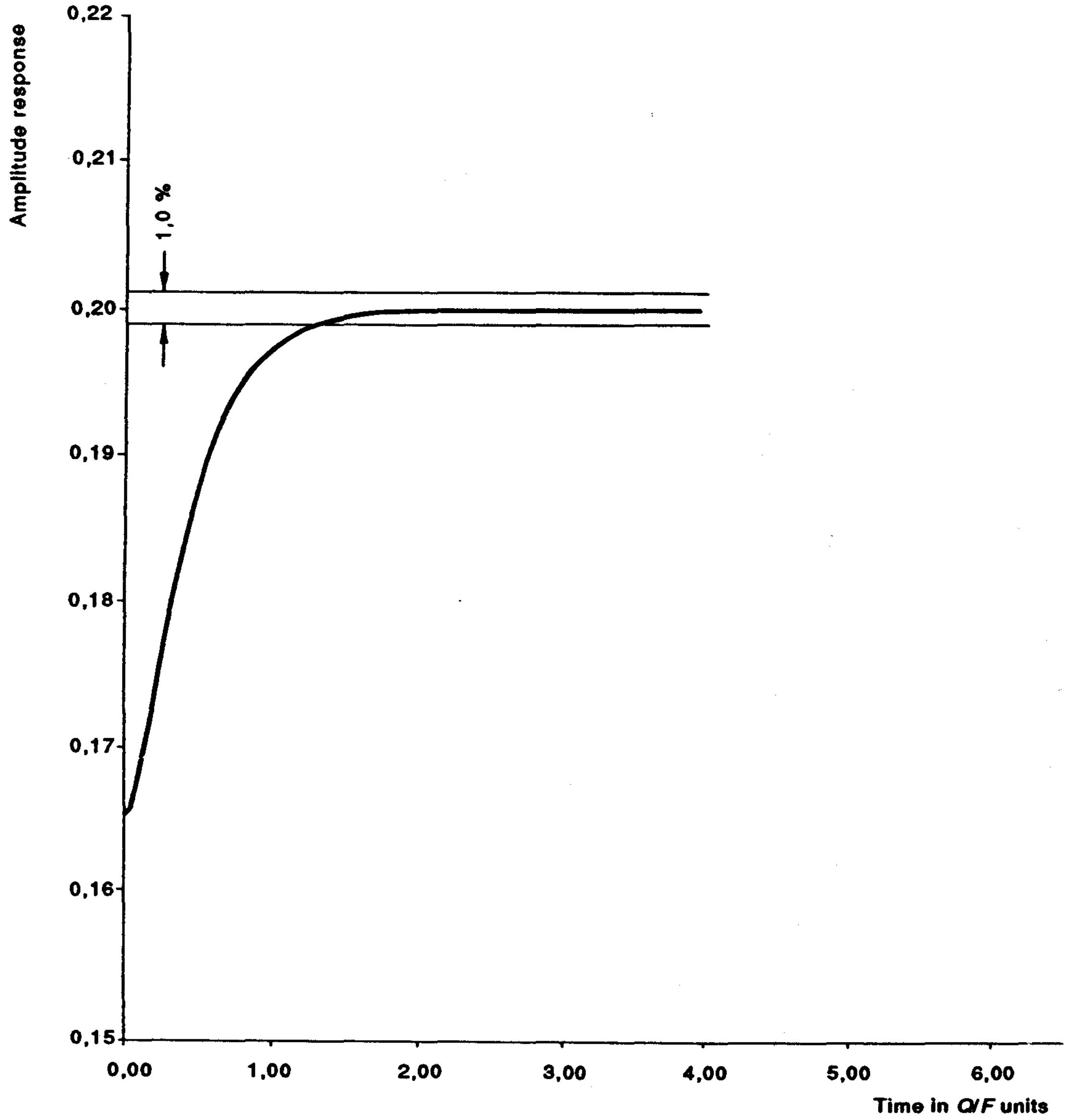


Figure 18 - Amplitude response of 75 kHz flexure resonator in 50 Ω system

Resonator f_s (kHz) = 75,565
Resonator Q = 120 000
Initial frequency from f_0 (H:) = −0,500
Frequency step (Hz) = 0,50
(Q/F), seconds = 0,68059

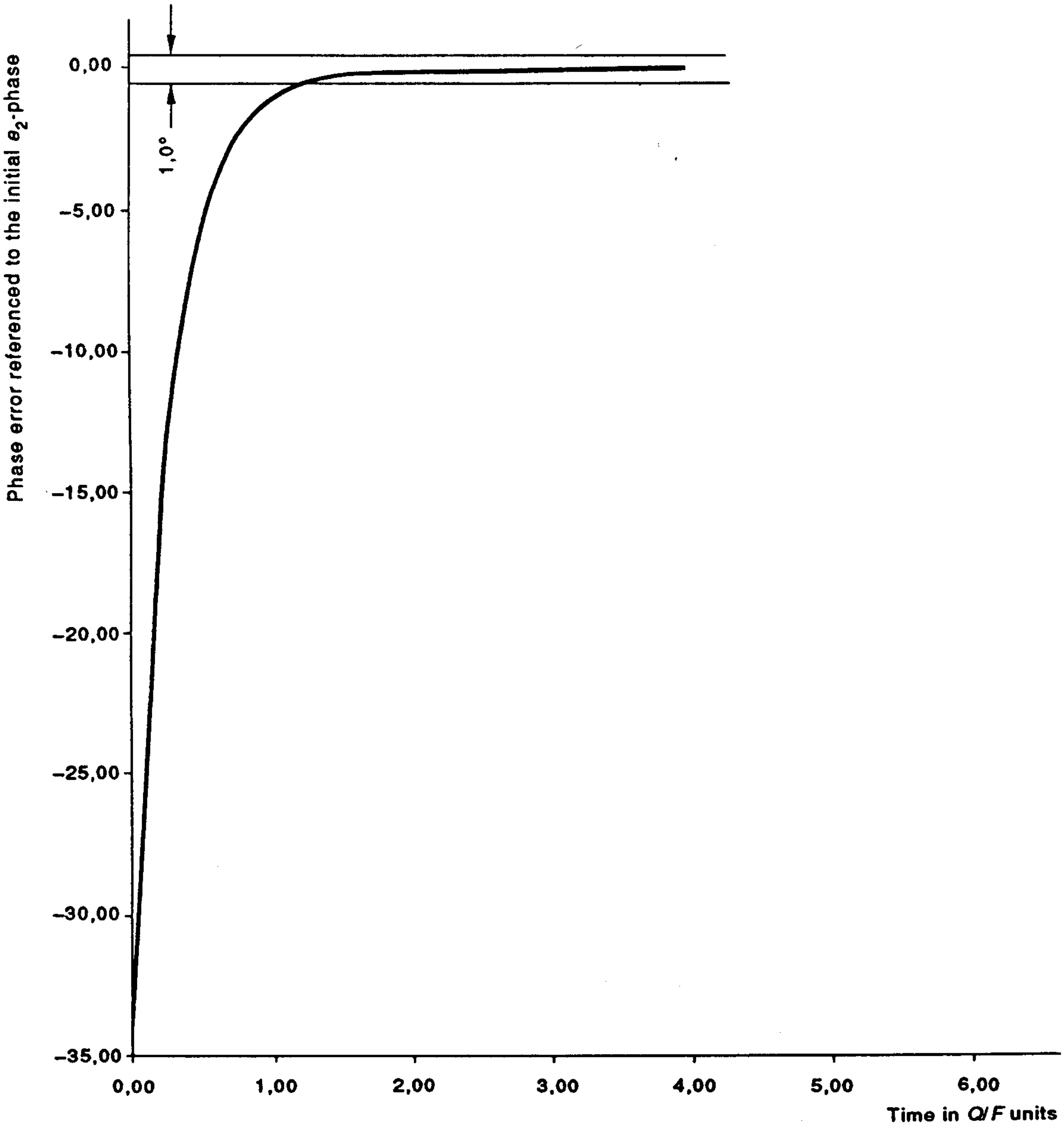


Figure 19 - Phase response of 75 kHz flexure resonator in 50 Ω system

Annex A

Classification of quartz crystal unit measurement systems

Electrical parameters of quartz crystal units under constant measuring conditions may be classified into three distinct groups:

i) Parameters characterizing desired (main) resonance; these parameters associated with the main motional arm of the equivalent circuit are of major importance.

ii) Parameters characterizing unwanted modes.

iii) Parameters characterizing the remainder of the equivalent circuit.

In some cases the so-called "load" parameters characterizing the equivalent circuit of a quartz crystal unit connected in series with an external circuit (usually capacitive) are also needed.

In the general case the quartz crystal unit must be treated as a three-terminal network, the third terminal being in the typical case a metal enclosure, which should be grounded. Three types of connection of the crystal unit are possible:

- one-port (two-terminal) connection in which one of the pins (leads) is grounded while the enclosure is floating;
- one-port (two-terminal) connection in which one of the pins (leads) is grounded and the enclosure is also grounded;
- two-port (three-terminal) connection in which only the enclosure is grounded.

The true values of the motional arm parameters of the quartz crystal unit equivalent circuit (for the main resonance: series resonance frequency f_s, motional resistance R_1 and motional capacitance C_1 or inductance L_1) are practically independent of the type of connection. However, the type of connection strongly influences the distributed (static) capacitances C_{AB}, C_{AH} and C_{BH}.

In the one-port connection, the effective shunt capacitance C_0 is to a first approximation the sum of the capacitance C_{AB} between the pins of the unit and the capacitance C_{AH} (or C_{BH}) between the ungrounded pin and ground. The influence of distributed capacitance is different in various measuring methods and different applications, so it is important to specify the crystal unit lead connection to be used.

In general, the characterization of a quartz crystal unit requires many rather complex measurements to be made at different frequencies near series resonance, to form an estimate of the equivalent circuit parameters which will best approximate the electrical behaviour of the unit. Fortunately, in most cases only a few of the crystal unit equivalent parameters need to be determined, particularly in the production environment.

The two most important parameters are: the series resonance frequency f_s and the motional resistance R_1. In a large number of cases, these may be approximated by measurement of zero-phase frequency f_r and zero-phase insertion resistance R_r. These latter two parameters may be measured with a limited accuracy by simple and fast *single frequency* methods (see clause 7).

More complex characterization of crystal units requires the use of several measurement frequencies, so *multi-frequency* methods are used.

From the point of view of general principles the most important measuring methods may be classified as follows:

i) *Oscillator methods* (also called active methods) in which the frequency of oscillation of special oscillator circuits, into which the crystal unit to be measured is connected, is measured and assumed to be the zero-phase frequency of the crystal unit.

ii) *Transmission methods* in which the crystal unit parameters are determined indirectly from measurements of the transfer function of the network formed by connecting the crystal unit (enclosure grounded) into a resistive network. Transmission methods may be divided into four sub-groups:

a) *Extremum transmission methods* (ETM) in which only information about the magnitude of the transfer function is used. The crystal unit frequency is identified as that at which the extremum (maximum) output voltage occurs.

b) *Phase transmission methods* (PTM) in which information about the transfer function phase is used. The crystal unit frequency is identified as that at which the output voltage phase is the same as that obtained during preliminary calibration (in the ideal case, the output voltage is in phase with the input voltage). In these methods amplitude information is not needed to establish frequency of the unit, but must be obtained if the insertion resistance is to be calculated.

Measuring sets using π- or T-transmission networks are the most important examples of equipment used for ETM or PTM.

c) *Vector transmission methods* (VTM) in which information about both the amplitude and phase of the transfer function is needed. In contrast to the ETM and PTM, which are fundamentally single frequency measurements, VTM typically require measurements at several frequencies near resonance so that motional capacitance (or inductance) may also be determined.

d) *Scattering parameter methods* (SPM) in which all four of the two-port scattering parameters of the three-terminal crystal unit connection are determined, and fully corrected for linear errors in measuring system and fixtures, at several frequencies near series resonance of the device. Such measuring sets require the use of dual-directional couplers and vector detectors, such as those incorporated in network analyzers.

iii) *Impedance (admittance) measuring methods* in which one-port quartz crystal unit parameters are determined using the vector values of the crystal unit impedance (admittance) measured at several frequencies near resonance. The method of calculation is the same as for the SPM above, but the crystal unit is connected as a one-port (with one pin/lead grounded). Two sub-groups of impedance measurement may be distinguished:

a) *Direct immittance methods* (DIM) in which equipment is used which reads out directly impedance (or admittance) values (e.g., various bridges or vector immittance meters).

b) *Reflection coefficient methods* (RCM) in which the quartz crystal unit parameters are determined from the vector values of the reflection coefficient of the crystal unit connected to a system port of known impedance, at several frequencies.

Various equipments measuring the complex reflection coefficient may be used in RCM. The most important are: sets containing directional coupler (or reflectometer) with a vector voltmeter, impedance meters utilizing directional bridges and some types of vector network analyzers.

Motional capacitance (inductance) may be calculated utilizing measurements of quartz crystal units at more than one frequency. Most important are three groups of methods:

i) *Load capacitor methods* (LCM) in which changes in resonance frequency due to the connection of load capacitances in series with the crystal unit are measured, and the motional capacitance calculated from the frequency difference.

ii) *Transfer function methods* in which frequencies corresponding to chosen points on the transfer function versus frequency curve of the transmission network containing the crystal unit are determined. Two sub-groups of these methods are the most important:

a) *Phase offset methods* (POM) in which two frequencies corresponding to two equal (but opposite in sign) values of transfer function phase are measured.

b) *Magnitude offset method* (MOM) in which two frequencies on opposite sides of the crystal unit resonance frequency with the same chosen value of transfer function magnitude are measured.

iii) *Admittance (impedance) methods* in which frequencies corresponding to chosen points of the admittance (impedance) versus frequency curve are measured. The most important sub-groups of these methods are:

a) *Immittance phase methods* (IPM) in which frequencies corresponding to chosen values of crystal immittance phase are used to calculate motional capacitance C_1 (motional inductance L_1).

b) *Immittance magnitude methods* (IMM) in which frequencies corresponding to chosen values of crystal unit immittance magnitude are used to calculate C_1 (L_1).

c) *Computer aided methods* (CAM) in which various algorithms are used to estimate C_1 (L_1) from the immittance values measured at several frequencies near the series resonance frequency of the crystal unit. One of the more important of these methods uses the slope of the motional arm reactance versus frequency curve at the point of zero reactance.

The effective shunt capacitance C_0 (for one-port quartz crystal unit connection) or the three capacitances $C_{AB} = C_0$, C_{AH} and C_{BH} (for two-port connection) are typically measured at low frequencies using appropriate capacitance bridges (LFM). In some measurement methods it is possible to measure the values of these capacitances at frequencies near the nominal frequency of the quartz crystal unit (HFM); this possibility is important for crystal units operating at high frequencies (i.e. 100 MHz or above) as the effective values of C_0 change with frequency due to stray inductances and capacitances of the mounting system.

TABULATION OF MEASURING METHODS

(A table of measuring methods is given on pages 93 to 97)

General assumptions:

- the main reason for the measuring method tabulation is to facilitate the preliminary choice of method;
- the structure of the table should allow the addition of new methods;
- the table should contain all the methods recommended or considered by IEC Technical Committee No. 49*;
- other methods used in practice in various countries and recommended by national standards or industrial standards should also be included;

- the table should be maximally concise.

The accuracy of quartz crystal unit parameter measurements depends on many factors, including both the effects of other parameters of the crystal unit and the characteristics of the measurement equipment used. Among the most important factors are:

- nominal frequency of the crystal unit;
- crystal unit quality factor;
- effective shunt capacitance of the crystal unit;
- uncontrolled stray reactances associated with the test fixtures and the crystal enclosure;
- temperature of the crystal unit and the measuring equipment;
- control of the drive level applied to the crystal unit during test.

Due to the very broad range of parameter values for quartz crystal units of various designs it is not possible to give accurate estimates of the accuracy obtainable with a particular method of measurement. Instead, it is proposed to use in the table three grades of accuracy: low, medium and high.

For typical quartz crystal units in the frequency range from about 1 MHz up to approximately 100 MHz intended for use in crystal-controlled oscillators "low" corresponds to frequency accuracy not better than about 5×10^{-6}; "medium" to a range of accuracies of about 1 to 5×10^{-6} and "high" to accuracies better than about 1×10^{-6}.

Abbreviations used:

General:

1P = crystal unit measured in one-port configuration;

---

* See the inside and outer back covers of this standard.

2P = crystal unit measured in two-port connection;

( ) = frequency range in megahertz;

1F = one-frequency method;

2F = two-frequency method;

3F = three-frequency method;

MF = multi-frequency method;

I: = method intended for measurement of the quantity given after the column;

U = method useful but not especially intended (in most cases existing documents do not specify detailed measuring procedures and accuracy is often unknown or difficult to determine);

low
medium = comparative rating of measurement accuracy.
high

Frequencies:

f_s = series resonance frequency $f_s = \dfrac{1}{2\pi\sqrt{L_1C_1}}$;

f_r = resonance frequency (zero insertion phase);

f_m = frequency of maximum admittance;

f_{mT} = frequency of maximum transmission;

f_{nT} = frequency of minimum transmission;

f_φ = frequency of transfer function zero phase;

f_L = load resonance frequency;

f_N = unwanted mode frequency.

Resistances:

R_1 = motional resistance;

R_r = resonance resistance (insertion resistance at zero phase);

R_L = load resonance resistance;

R_N = unwanted mode resistance.

C_1/L_1 measuring methods:

LCM = load capacitor method;

POM = transfer function phase offset method;

MOM = transfer function magnitude method;

IPM = immittance phase method;

IMM = immittance magnitude method;

CAM = computational method.

C_0 measuring methods:

LFM = low frequency method (below 1 MHz);

HFM = high frequency method (near crystal unit operating frequency or above).

Cross-reference tabulation of measuring methods of quartz crystal unit parameters

(Asterisks [*] in columns 1 to 7 refer to notes in column 8)

Type of method	Main resonance			Unwanted resonances	C_0	Load resonance frequency f_L and resistance R_L	Notes
	Frequency	Resistance	$C_1/L_1/Q$				
1	2	3	4	5	6	7	8
OSCILLATOR METHODS	1F	1F	3F or 2F			1F	
Crystal impedance meters * 2P	I: f_r low	I: R_r low	U(LCM) low	-	-	U: f_L, R_L low	* Depend on the type of CIM; test fixtures and load capacitors are not specified
TRANSMISSION METHODS							
Extremum transmission (ETM) with π-type network 2P	1F	1F	3F	1F		1F	
(≤ 30 MHz) IEC Publication 302	I: $f_{mT}<f_m$ medium	I: R_1 medium	I(LCM) medium	U: f_N,R_N medium	-	U: f_L, R_L low	π-network and load capacitors are not specified
(1 - 30 MHz) IEC Publication 444-4*	-	-	U(LCM) medium	-		U: f_L,R_L high	* Intended for PTM
(1 - 125 MHz) IEC Publication 444*	U: $f_{mT}<f_m$ medium	U: R_1 medium	U(MOM) medium	U: f_N,R_N medium			* Intended for PTM
With T-type network 1P	1F	1F	3F	1F	-	1F	
(1 - 60 MHz) Polish Industrial Standard	-	-	-	-	-	I: f_L, R_L high	With internal constant C_L value
(1 - 125 MHz) Polish Industrial Standard	I: $f<f_m<f_s$ medium	I: R_1 medium	U(MOM) medium	U: f_N,R_N medium			* High using FM variant
With special bridge network IEC Publication 283	U	U	-	I: f_N,R_N medium*			* High for lower frequencies

1	2	3	4	5	6	7	8
Phase methods (PTM) with π-type network 2P	1F	1F	3F	1F		1F	
(1 - 30 MHz) IEC Publication 444-4			U(LCM) medium			I: f_L,R_L high	
(1 - 125 MHz) IEC Publication 444	I: f_r medium*	I: R_r medium		U: f_N,R_N low	U(HFM) low		* High for lower frequencies
(1 - 200 MHz) IEC Publication 444-1			I(POM) medium				
(1 - 200 MHz) IEC Publication 444-3	I: f_s medium	I: R_1 medium	I(POM) medium	U: f_N,R_N medium			With selective external C_0 compensation
With T- type network 1P	1F	1F	3F	1F			
(≤30 MHz) Polish Industrial Standard	U: f_r medium	U: R_r medium	I(LCM) high			U: f_L,R_L high	With five internal switched load capacitors
(1 - 60 MHz) Polish Industrial Standard						I: f_L,R_L	With internal constant C_L value
(1 - 125 MHz) Polish industrial standard	I: f_r high	I: R_r medium	U(POM) medium	U: f_N,R_N medium			
Vector methods (VTM) 2P	MF	MF	MF	MF	MF	MF	
(≤0,1 MHz) USA Industrial Standard	I: f_s high	I: R_1 high	I(CAM) high	U: f_N, R_N high		U: f_L,R_L	Computer-aided
(1 - 125 MHz) IEC Publication 444	I: medium*	I: medium*	I(CAM) medium	U: f_N, R_N medium	U(HFM) low	U: f_L, R_L medium	Computer-aided * High for lower frequencies
f_r- meter method	I: f_r high	I: R_r					Computer-aided
S-parameter methods 2P (+)	MF	MF	MF	MF	MF	MF	Computer-aided
(0,1 - 1 000 MHz) USA Industrial Standard	I: f_s high	I: R_1 high	I(CAM) high	U: f_N,R_N high	I(HFM) C_0, C_{AH}, C_{BH} high	U: f_L, R_L	Test fixtures are not specified

1	2	3	4	5	6	7	8
IMMITTANCE METHODS *Direct immittance methods (DIM)**							* Frequency ranges depend on the type of equipment
LF capacitance bridges 2P					1F I: C_0, C_{AB}, C_{BH}, high		Test fixtures are not specified
HF bridges	MF U: f_s high*	MF U: R_1 high*	MF U(CAM) high*	-	MF U(HFM) high*	MF U: f_L, R_L high*	Test fixtures are not specified * Or medium, depending on accuracy of bridges
1P	1F(IMM)	1F(IMM)	3F	1F(IMM)	1F		Test fixtures are not specified
Vector impedance-meters	U: f_m medium*	U: R_1 medium*	U(IMM) medium*	U: f_N, R_N medium*	U(HFM) medium	-	* Depend on accuracy of vector impedance-meter
1P Vector impedance-meters	1F(IPM) U: f_r medium*	1F(IPM) U: R_r medium*	3F U(IPM) medium*	1F(IPM) U: f_N, R_N medium*	1F U(HFM) medium		* Depend on accuracy of vector impedance-meter
Reflection coefficient methods (RCM) 1P (+)							
(0,1 - 1 000 MHz) USA Industrial Standard	MF I: f_s high	MF I: R_1 high	MF I(CAM) high	MF U: f_N, R_N high	MF I(HFM) C_0, high		Computer-aided Test fixtures are not specified

(+) Comparable precision can be obtained using transmission fixtures similar to the IEC π-network by the use of computerised error correction methods.

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